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HANDBOOK FOR RELIABILITY AND MAINTAINABILITY MONITORS

G. H. Allen, et al

Technical Requirements and Standards Office
L. G. Hanscom Field,
Bedford, Massachusetts

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TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-64-616

DECEMBER 1964

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TECHNICAL REQUIREMENTS AND STANDARDS OFFICE
ELECTRONIC SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
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FOREWORD

Various regulations, such as, AFR 80-5 and 69-29, and AFSCR 80-1 and 80-9 define AF policy matters in Reliability and Maintainability (R/M). Equipment and management specifications such as, MIL-R-27542 and MIL-M-26512 establish program or equipment requirements, but the AF literature generally lacks guidance type documents advising the SPO or procurement activities on how to establish or manage an R/M Program.

Availability of specialized training in these fields is limited, with only a few colleges offering courses. Manpower limitations further complicate the training programs since personnel cannot be spared for long periods of time to take those courses that are available.

The purpose of this TDR is to provide ready reference in a single volume, information, guidance, and procedures on ESD R/M policy. This volume is organized into sections. Each deals with a given facet of R/M that the ESD R/M staff has noted as a problem area, potential or actual.

This document is not a study in depth, nor is it to be considered as a complete and final text. Rather it covers present ESD philosophy and provides needed guidance. As additional work is done in the R/M areas, this volume will be revised or additional sections will be added. The sections contained herein were prepared during the 1963-1964 period by ESTE staff members; G. H. Allen, Major J. R. Barton, R. M. DeMilia, Capt G. Grippo, and J. E. Horowitz.

ABSTRACT

The ESD Reliability and Maintainability (R/M) Staff originally prepared a series of pamphlets dealing with R/M matters during 1963-64. These have now been combined into a single handbook for ready reference and assimilation by ESD personnel associated with R/M programs. Each section of this handbook deals with a particular problem area in R/M matters and suggests methods of initiating and operating an R/M program. The material covered ranges from the basic elements of establishing a program thru the engineering requirements to be evaluated in design reviews. The overall operations involved in monitoring of a contractors program are defined. Several sections deal with the mathematical aspects of Reliability decision making including construction of probability of acceptance curves. Specific areas covered in this TDR are listed in the Table of Contents.

REVIEW AND APPROVAL

This Technical Documentary Report has been reviewed and is approved.

FRANK E. BRANDEBERRY
Colonel, USAF
Chief, Tech Rqmts & Stds Off

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Edward J. Pinney, Lt Col, for

FRANK E. BRANDEBERRY

Colonel, USAF

Chief, Tech Rqmts & Stds Off

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SECTION I

GUIDANCE ON PROPOSAL CONTENT FOR RELIABILITY AND MAINTAINABILITY IN SYSTEM / EQUIPMENT PROCUREMENTS

FOREWORD

The purpose of this section is to provide guidance to SPO Reliability and Maintainability (R/M) Monitors in establishing requirements for the R/M part of a system/equipment proposal.

Specific items which bidders must discuss in proposals are presented. A brief discussion is presented on each item. This section amplifies those instructions contained in PMI 1-9, Preparation of Requests for Proposals for Systems, 25 January 1963.

SECTION I

CONTENTS

SUBJECT PAGE

GUIDANCE ON PROPOSAL CONTENT FOR
RELIABILITY AND MAINTAINABILITY IN
SYSTEM/EQUIPMENT PROCUREMENTS

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1. Introduction:

Current approaches to the disciplines of Reliability and Maintainability (R/M) include the insertion of quantitative requirements and R/M specifications in Request For Proposal (RFP) documents which deal with system/equipments.

Responses to these items by potential contractors have been varied and, at times, have left important R/M considerations unanswered.

The purpose of this pamphlet is to set forth the R/M items which a potential contractor is expected to cover in a technical proposal. In addition, significant material to be presented under each item is discussed.

2. R/M Organization:

A bidder's proposal should identify the position of his R/M Group or Section within his overall organizational structure. Usually, the R/M Group either is positioned as a line activity under engineering or combined with Quality Control (and perhaps other disciplines) to form a Product Assurance Department.

Most large companies will have a R/M Staff Officer (perhaps, Vice-President, Reliability and Quality Control) who is responsible for generating overall R/M policy and standard operating procedures.

The main concern in studying a bidder's R/M organization is to determine whether or not the proposed organization will be responsive to the overall R/M program requirements, sensitive to problem areas, and able to contribute to the formulation of design criteria and the control of design for reliability and maintainability.

Its ability to perform, in accordance with the above paragraph, is also a function of its personnel capability-mix. Since R/M encompasses a wide variety of tasks, ranging from complex modeling techniques to design criteria, a bidder must be in a position of stating the quality and quantity of people available to perform the proposed R/M program.

3. Prediction of R/M:

It is expected that a bidder will make a first determination or prediction of the R/M capability of his proposed system/equipment design and compare the results with the quantitative R/M requirements. All equations employed in the computations and any mathematical assumptions must be clearly stated. In addition, failure rate data sources and a discussion of their adequacy must be presented.

The prediction serves to identify possible R/M weaknesses in a proposed system/equipment design. A bidder should be able to indicate how these weaknesses are to be overcome. For example, a magnetron, even when operated conservatively, has a high (as compared to a simple resistor, for example) inherent failure rate and in a simple reliability series system/equipment influences considerably the resultant system/equipment failure rate A bidder should indicate what compensating features (such as, redundant replacement or malfunction protection) he intends to introduce into his design to minimize the influence of this or other high failure rate items.

Another important consideration is the proposed preventive maintenance cycle. Missions can be interrupted by unscheduled (failures) as well as scheduled maintenance. The problem is the unavailability of system/equipment for mission accomplishment during either type of maintenance.

The manner in which support is programmed, after system/equipment transition, is influenced by required preventive maintenance. Bidders should be expected to discuss the amount (frequency), type, and duration of preventive maintenance required for their proposed system/equipment designs.

4. Evidence of Past R/M Accomplishments:

R/M quantitative requirements have been inserted into Government contracts since the early 1950's. It is to be expected that bidders will be able to cite performance on past contracts and state how successful they were in meeting and exceeding imposed quantitative requirements. Since programs differ in degree of sophistication, a brief description of overall program requirements should be included with each program cited.

5. R/M Design Review Schedule:

Potential R/M problems must be detected and corrected in the early stages of a system/equipment program. Conservative cost estimates indicate that system/equipment problems which remain unresolved during design, and finally are resolved during operational usage, will require an expenditure of one thousand times as many dollars as during design (to say nothing of the inconvenience of having system/equipments in a down-state while modifications are performed).

The following types of design reviews are expected to be scheduled by a potential contractor:

a. Concept, to investigate and decide on the design approaches to be taken to satisfy the quantitative R/M requirements.

b. Component Part Selection and Application, to insure that parts having histories of low failure rates are selected to be incorporated into system/equipments and that conservative application of these parts takes place.

c. Electrical, to insure minimization of drift type failures, simplicity of design, and adequacy of failure detection devices.

d. Mechanical, to insure proper packaging, design of the cooling system, and overall physical layout for ease of maintenance.

e. Producibility, to alert manufacturing personnel to the possibilities of unique or unusual manufacturing techniques that may be required during the manufacturing cycle.

The success of a design review is partially dependent on the participants. Most companies will assign design review responsibilities to senior or staff engineers. Usually, there will be a permanent design review chairman who will draw on the technical resources of a company as needed.

Minutes of meetings are expected to be maintained and corrective action recommendations developed. However, a decision as to modification of a design is usually left to the appropriate design engineer, unless the error or deficiency is of such a nature as to warrant referral to management.

A potential contractor's proposal should be carefully reviewed to determine the adequacy of his design review activity in terms of the following criteria:

a. Timeliness, reviews occur before drawing release to production.

b. Frequency and variety of reviews.

c. Responsibility for corrective action follow-up.

d. Method of organizing reviews with attention to the type of personnel assigned review responsibility.

6. Description of Proposed R/M Program:

A bidder is expected to define his complete proposed R/M Program in terms of:

a. Tasks to be accomplished.

b. Task descriptions.

c. Time-Phasing.

d. Significant milestones.

e. Responsibility for task accomplishments.

Item d is important since it serves to establish program monitoring points or times at which contractor progress can be assessed and any necessary redirection given by the procuring agency. Monitoring of contractor programs is a definite procuring agency responsibility under current Air Force Regulations (AFRs).

RFPs usually contain those elements of an R/M Program which are compatible with the overall system/equipment procurement. ESDP 80-2, General Requirements for a Reliability and Maintainability Program Plan for Electronic Systems, 15 August 1963, has set forth the basic R/M elements which are applicable to all system/equipment procurements.

Two elements or tasks of a proposed program must be defined in some depth, namely, subcontractor management and corrective action management.

Serious system/equipment R/M problems occur, if prime contractors do not provide a subcontractor management activity. This activity should encompass:

a. Incorporation of quantitative R/M requirements into all specifications for subcontracted equipment.

b. Demonstration requirements.

c. Provisions for a R/M Program which is compatible with the Prime Contractor's Program.

d. Scheduled monitoring.

It is obvious that the collection, processing, and analyzing of R/M data and the holding of design reviews as such cannot improve the R/M capability of systems/equipments. It is necessary to supplement these tasks with a corrective action management task. A bidder should be prepared to outline his corrective action procedures. These procedures should include a discussion of his R/M data collection feedback system (see, for example, ESDP 80-3, General Requirements for a Data Collection and Evaluation System for Electronic Systems, 1 November 1963) and specifically should indicate the provisions by which his R/M Group is assured the opportunity to review and assess the effect of all changes on system/equipment R/M capability.

Since design or inherent reliability must be protected from unnecessary degradation during manufacturing, a bidder should discuss his factory quality control system with particular attention to any unique techniques which are to be employed to insure delivery of reliable equipment.

These techniques could involve testing samples of component parts to Acceptable Reliability Levels (ARLs) during incoming inspection, additional "burn-in" tests of major elements of equipment, specialized training courses to increase skill levels of personnel involved in manufacturing, etc.

7. <u>Discussion of Equipment R/M Demonstration Plans</u>:

The specification of quantitative R/M requirements for equipment involves consideration of statistical techniques to illustrate that the requirements in fact have been satisfied.

ESDP 80-5, Verification of Quantitative Reliability Requirements (Decision Criteria), 15 November 1963, sets forth some approved reliability demonstration techniques. An important consideration stressed in ESDP 80-5 is the quantification of the risks involved in making decisions about compliance to reliability requirements.

An acceptable model for decision-making purposes, under certain circumstances, is the Cummulative Poisson Distribution. This model has as basic inputs:

a. A fixed value for test time (T).

b. A value for mean-time-between-failure (MTBF, θ).

c. An allowable number of failures (C).

A choice of C should be made after a study of operating characteristic functions. Such functions relate the probability of acceptance to values of the ratio of "true" MTBF (θ_T) to contractual MTBF (θ). For any C, as this ratio increases in value, the probability of acceptance increases.

For example, assume a test time equal to a contractual MTBF. If C is set equal to zero, Table I indicates that an

<u>Table 1</u>
C=0

θ_T/θ	Probability of Acceptance (Approx.)
1/4	2%
1/2	14%
1	37%
2	61%
4	78%
6	84%
10	90%

equipment would have to be delivered for test with a "true" MTBF ten times the value of the contractual MTBF in order to have a 90% probability of acceptance. Such a situation probably would result in a bidder requesting that C be raised to another value. If C were set equal to one, for example, the probability of acceptance values would be as indicated in Table 2.

Table 2
C=1

θ_I/θ	Probability of Acceptance (Approx.)
1/4	10%
1/2	42%
1	74%
2	91%

Table 2 numbere indicete that an equipment would have to be delivered for test with e "true" MTBF two times the value of the contrectual MTBF in order to heve et leest e 90% probability of ecceptance.

The arithmetic elso determines the procuring ectivity risk or probebility of accepting an unsetisfactory equipment. For example, Teble 2 numbers indicete thet there is e 10% probability thet an equipment with e "true" MTBF of only one-fourth the required will be accepted; i.e., experiences one or less failures during the test. On the other hand, e bidder could have an equipment which had e "true" MTBF twice the value of the contrectual MTBF and still heve e 9% probebility thet the equipment would be rejected; i.e., experience more than one failure during the test.

Additional computations could be performed by setting test time equal to multiples of contrectual MTBF. The point of this discussion is to alert proposal evaluetors to the problem of selecting e C value with due regard to the risks involved.

Mainteinebility demonstretion involves simuleting equipment feilures to develop e statisticelly significent repair time sample size. While MIL-M-26512 outlines e method for mainteinebility demonstration, other methods proposed by bidders should be examined for their ecceptebility. The important consideretion is thet en approved quantitetive decision rule be developed prior to the commencement of demonstretion.

8. Summary:

A bidder is expected to consider the following R/M criterie in preparing his system/equipment proposal:

e. Prediction of the R/M cepability of his proposed system/equipment design with attention to potential R/M problem ereas and epproeches to problem resolution.

b. An in-depth discussion of design review sctivities, corrective ection management plans, and R/M demonstrstion techniques.

c. A task by task description of his proposed R/M Program. This description should include a time-phasing of appropriete milestone review points.

d. An identification of his R/M Organization, its cepability-mix, lines of communcietion and responsibilities.

e. A description of eccomplishments on past R/M Programs, compliance to quantitative R/M requirements, and an indicetion of the sophisticetion of cited overell system/equipment procurements.

SECTION II

GENERAL REQUIREMENTS FOR A
RELIABILITY AND MAINTAINABILITY
PROGRAM PLAN
FOR
ELECTRONIC SYSTEMS

SECTION II

GENERAL REQUIREMENTS FOR A RELIABILITY AND MAINTAINABILITY PROGRAM PLAN FOR ELECTRONIC SYSTEMS

FOREWORD

The purpose of this section is to provide guidance to SPO Reliability and Maintainability (R/M) Monitors in establishing general requirements for a contractor's "R/M Program Plan".

Underlying this section is a fundamental principle: ESD will not state to a contractor that an R/M program is to be performed in accordance with existing R/M specifications. Existing specifications are by necessity quite general in nature. Their requirements must be selected and defined on the basis of individual system/equipment procurements.

However, there is a set of fundamental R/M tasks that are considered mandatory for any system/equipment procurement. The exact depth of, and approach to, these tasks will of course, be dependent on individual system/equipment procurements.

It is recommended that the SPO provide the Using Command and the Logistics Command the opportunity to review and concur on the approach and plans for the R/M program. This will aid in avoiding difficulties in the Using Command accepting a system due to unresolved definitiong of R/M acceptability.

Assistance in defining R/M program requirements is given to SPOs by the Office of Primary Responsibility (OPR) in accordance with ESDR 80-2 and ESDR 80-4.

SECTION II

CONTENTS

GENERAL REQUIREMENTS FOR A RELIABILITY AND
MAINTAINABILITY PROGRAM PLAN FOR ELECTRONIC SYSTEMS

1. Basis of Requirement for a Reliability and Maintainability Program Plan:

MIL-R-27542, paragraph 3.3, and MIL-M-26512, paragraph 3.2, requires the preparation by a contractor and submission to the procuring agency of a reliability and a maintainability plan, respectively.

The Electronic Systems Division (ESD) discourages the submission of two plans; one for maintainability and one for reliability. This is the result of the unique operational requirements of systems assigned to ESD. These requirements involve a numerical expression for operational availability. The latter represents a simultaneous treatment of maintainability, expressed as a mean-down-time (MDT) statistic; and reliability, expressed as a mean-time-between-failure (MTBF) statistic.

ESD procures one combined program plan which must describe the methods by which a contractor controls both the MDT and MTBF characteristics of electronic systems beginning with the design phase of a system program. This plan can be referred to as an "Availability Program Plan."

2. Format of Program Plans:

First, ESD expects a program plan to provide:

a. The tasks or work elements to be accomplished.

b. A description of the work to be accomplished under each task (task description).

c. The time-phasing of each task.

d. The manloading assigned for the accomplishment of each task.

e. Appropriate program plan milestone review points.

Second, as exhibits or attachments to a plan, ESD expects to have a contractor describe his:

a. Design review system, its method of operation, responsibilities, and authority.

b. Corrective action system, including his data collection system, and proposed computational ground rules.

c. Change order control system, with particular attention to the method by which his R/M organization has the opportunity to review all design changes for quantitative effects.

Third, as exhibits or attachments to a plan, ESD expects to have a contractor indicate the position of his R/M operation within his management structure, describe the organization of this operation, and indicate the channels of communication between this organization and design engineering, quality control, test engineering, and components engineering.

Fourth, ESD discourages the preparation of program plan reports on offset printing with elaborate covers. Hecto or engineering letter type reports are preferred for purposes of cost reduction.

3. Fundamental Reliability and Maintainability Program Elements or Tasks:

a. The family of reliability specifications (MIL-R-27542, MIL-R-27070, MIL-R-26474) and the maintainability specification, MIL-M-26512, actually describe a series of reliability and maintainability tasks or work elements. Depending on the type of procurement, the nature of the quantitative requirements, and the importance of the system/equipment mission, ESD will decide on the reliability and maintainability tasks to be accomplished by a contractor. However, there are certain R/M tasks which are considered fundamental to the establishment of an acceptable R/M program. These tasks can be grouped for convenience under the following general headings:

(1) Mathematical/Statistical Analysis.

(2) Design Assistance.

(3) Assessment and Verification.

(4) Test Planning Assistance.

(5) Subcontractor Management (For Prime Contractors).

(6) Failure Analysis.

(7) Corrective Action Management.

(8) Manufacturing and Field Support.

(9) Reports.

b. Task Descriptions:

(1) Mathematical/Statistical Analysis. ESD requires the preparation of a mathematical model which allows the computation of the appropriate R/M statistics describing the system under development. A first step in the construction of such a system model is the performance of an "equipment block analysis." This analysis will indicate the possible modes of operation or configurations which allow mission accomplishment. For equipment in reliability series, the block analysis results are obvious. However, for the more complex equipment configurations under development at ESD, the analysis is usually not routine. Following the block analysis, appropriate mathematical expressions will be written.

It is expected that the quantitative requirements will be apportioned over equipments, subassemblies, and critical or high failure rate piece parts. This apportionment actively serves as a design control. Design engineers are anxious to know the burden placed on their particular design by the overall quantitative requirements.

Several R/M predictions are expected to be produced during a program. The exact time-phasing of these predictions is a function of the overall program schedule. ESD will not be satisfied by just the reporting of a result. All computations will be supported by citing appropriate failure rate sources (such as, MIL-HDBK-217, "Reliability Stress and Failure Rate Data for Electronic Equipment"). If unique or contractor oriented failure rates are employed, ESD expects to have justification presented for their use. This justification will include:

(a) Method of data collection and reduction.

(b) System/equipment and operations over which the data was collected and analyzed.

(c) An adequate explanation of the use of any extrapolations or adjustment factors.

Statistical analysis will be performed in support of all test activities. This analysis serves to express quantitatively the R/M characteristics of system/equipment. In addition to such statistics as MTBF, MDT, and Availability, ESD recognizes the usefulness of the development of a reliability function - the statistical probability of no failures as a function of satisfactory operating time, and the maintainability function - the statistical probability that a system/equipment will be restored to a satisfactory operating condition as a function of down time. Initially, such functions may be constructed by application of non-parametric statistical techniques and eventually fitted to underlying probability density functions.

Before statistical computations take place, it is necessary that ESD and a contractor agree to computational "ground rules." Quoting of numbers without a thorough understanding of the techniques employed in their development is unacceptable to ESD.

A further important use of statistical analysis is the identification of "weak-links" in system/equipment and a support to the corrective action process.

(2) Design Assistance. A contractor's R/M organization is expected to supply design engineering with recommendations and techniques for designing reliability and maintainability into a system/equipment. As examples, techniques for designing reliability into a system/equipment are:

(a) Conservative application of component parts (appropriate margins of safety).

(b) Circuit simplification.

(c) Redundant replacements and/or alternate modes.

(d) Minimization of environmental/operational stress.

Formal engineering design reviews are required to be scheduled at significant points in a program. These reviews will range from parts list, part applications, fail-safe circuit practices, simplification of circuitry, use of standard circuits, mechanical and packaging considerations, to resolution of interface R/M problems of equipments. ESD expects to participate in selected reviews and a contractor must alert ESD ten days prior to conducting any review. In addition, a contractor must maintain complete records of each review and furnish them to ESD upon request. A summary of the results of each review will be made as part of monthly progress reports.

All non-ECPs and ECPs will be reviewed for quantitative effects on reliability and/or maintainability.

Continuous liaison between a contractor's R/M and design organization will be maintained to assure that timely corrective action is taken on R/M "weak-links."

(3) Assessment and Verification. It is absolutely essential that a contractor's R/M Program provide for a demonstration that the contractual quantitative reliability and maintainability requirements have been achieved and/or exceeded. The means by which this verification is to be accomplished will be set forth by ESD. Usually, due to the complexity of electronic systems, a combination of analytical and test methods is employed.

The contractor's R/M plan will provide for the collection of failure, downtime, and repair time data. The data collection format will be subject to the approval of ESD. Statistical reduction of collected data has been discussed in paragraph 3b(1) above.

(4) Test Planning Assistance. A contractor's R/M organization will participate in the development of all test plans, especially those involved with category testing, for systems/equipments. Particular emphasis is necessary on:

(a) The statistical and engineering validity of plans, e.g., the properties of randomization and replication, are essential to a valid plan.

(b) The timeliness and accuracy of the failure data collection system.

(5) Subcontractor Management. Prime contractors will be required to:

(a) Incorporate quantitative R/M requirements in subcontracted equipment specifications.

(b) Assure that each subcontractor has an R/M program which is compatible with the overall R/M program. Subcontractor progress will be periodically reviewed.

(c) Attend and participate in subcontractor engineering design reviews.

(d) Review subcontractor predictions and computations for accuracy and correctness of approach.

(e) Furnish subcontractors with failure and maintainability data resulting from tests.

(f) Require subcontractor progress reports.

(g) Review subcontractor test plans for accuracy and correctness of approach.

(h) Assure that subcontractors have, and are pursuing, a vigorous corrective action effort on causes of unmaintainability and/or unreliability.

ESD is aware that causes of unmaintainability and/or unreliability can arise from poor communications and monitoring of subcontractors by prime contractors. ESD will periodically visit subcontractors to determine the effectiveness of prime-subcontractor R/M program.

(6) Failure Analysis. Maintenance of records or statistical analysis of data is not completely sufficient to support a corrective action program or system. Record analysis must be supplemented by engineering laboratory analysis of selected failed component parts, units, and/or assemblies. To serve a useful purpose, the failure analysis effort must be carefully integrated into the corrective action system.

(7) Corrective Action Management. Design reviews, data analysis, and failure analysis are not completely adequate to improve the reliability or maintainability of a system/equipment. These actions must be supplemented by a corrective action system that:

(a) Assigns responsibilities for corrective action.

(b) Assigns suspense dates for completion of the required action.

(c) Provides follow-up to assure that actions are actually taken.

(d) Assesses the quantitative affect on reliability and/or maintainability by the action.

(e) Assures that R/M design principles are followed in any proposed modification.

(f) Determines the effectivity of a "fix".

(g) Maintains a problem or "weak-link" list by contractors. This list will contain:

1. Definition or statement of a problem.

2. Corrective action contemplated.

3. Action agency or responsibility for problem resolution.

4. Effect of problem on reliability and/or maintainability.

5. Action completion date.

An effective contractor management tool is an R/M Improvement Committee. This committee, composed of members from organizations involved in obtaining corrective action, e.g., design engineering, components engineering, quality control, purchasing, reliability, etc., meets periodically to assure that progress is being made to resolve "weak-links" and to assign responsibility on additional problems.

ESD recognizes the complexity of R/M problems and the necessary interactions between organizational groups in order to obtain timely corrective actions. Such a committee, therefore, is recognized as a useful element of a contractor's corrective action system.

(8) Manufacturing and Field Support. The R/M designed into equipments must not be allowed to be significantly degraded during the manufacturing and site installation phases of a system/equipment program by the introduction of "Q.C. type of failures". Furthermore, the downtime of a system/equipment must not be allowed to increase because of improper provisions for replacements (spares) and/or the unreliability of AGE.

Technical manuals have also been a source of unreliability and/or unmaintainability. Shipping and storage practices have produced additional failures into a system/equipment.

Improper positioning of equipment within a shelter has introduced "human-caused failures" and contributed to increased system/equipment downtime. Therefore, during manufacturing and installation, ESD will require a contractor to conduct an "R/M assurance support effort".

In addition, to assure the timely and accurate transmission of failure and maintainability data from tests on site, the contractor will assign R/M engineers to a site who are charged with the responsibility of data collection. These engineers will also make a preliminary classification of each failure as to cause, e.g., design error, component part, mishandling, operational error, manufacturing or fabrication, etc., and affect, e.g., lethal, major, minor, and no effect. This classification will be reviewed by the main R/M organization as part of the determination of "weak-links" and assignment of corrective action responsibility.

The on-site R/M engineers will be kept informed of the progress made in taking corrective actions.

(9) Reports:

(a) ESD expects a contractor to summarize monthly his progress on each R/M task.

(b) Special reports will be required on mathematical model developments, predictions, demonstration plans and results, and design review results.

(c) ESD will request minutes of design review meetings, reliability indoctrination lectures, and failure analysis summaries.

(d) Whenever any of the above reports contain significant scientific or technical data the report will be prepared and published as an ESD Technical Documentary Report in accordance with Volume III, ESD Contractor Reports Exhibit 63-1.

ESD will require a contractor to indicate, as part of his program plan, submission dates for the above material.

4. Actions Required by ESD:

a. General R/M statements as: "Reliability will be in accordance with MIL-R-27542" or some other reliability specification, or "Maintainability will be in accordance with MIL-M-26512," present unsatisfactory guidance to potential contractors. It is necessary that an R/M program be designed to suit the needs of an individual system/equipment. The responsibilities for the general design of an R/M program are set forth in ESDR 80-2 and ESDR 80-4.

b. ESD will set the date for submittal of a contractor's proposed R/M program plan. A proposed plan will be thoroughly reviewed for its acceptability against the program design established by ESD.

c. Comments will be presented on the proposed plan either verbally, during a contractor guidance meeting, or in writing (or both). A resubmittal date for the plan will be established.

d. A contractor will receive formal notification of acceptance of the plan.

e. ESD will not give approval of a prime contractor's plan until each subcontractor's plan has been reviewed.

f. ESD will require that a definite schedule of program reviews be established. These reviews are in addition to attendance at contractor engineering design reviews.

APPENDIX I

Some R/M Program Interfaces

A contractor's R/M Program must be carefully integrated within his total effort, since the resulting reliability and maintainability characteristics of a system are influenced by system design, hardware or equipment design, test equipment, number and skill level of personnel, training, technical manuals and physical or operational environment. But, it is during the early system engineering phases of a program that an R/M Organization can contribute significantly to achievement of system requirements.

For example, ESD might state a system point availability requirement which is expressed as,

$$A = \frac{MTBF}{MTBF + MTTR}$$

To establish specific subsystem and major equipment R/M requirements, the system point availability requirement must be analyzed within a framework which includes:

a. Functional or performance requirements which dictate general design features.

b. Cost constraints which can be allocated between initial costs (equipment research and development, production, installation, training, technical manuals, special equipment and tools), and support costs which continue throughout the life of the system.

c. Time constraints including design, production, installation and training.

d. Personnel constraints which dictate the general skill level and number of personnel available for operating, controlling and maintaining the system.

e. Miscellaneous requirements and constraints, such as established support and logistic policies, environmental conditions, etc.

With considerations such as expressed in (a - e), it is obvious that allocation of a system point availability requirement to subsystems and major equipments must be cooperatively performed. Figure I suggests a simple flow by which reliability and maintainability considerations are included within the total system engineering decisions.

A number of hardware approaches have been derived as possible alternative methods for restoring a system to operation subsequent to a failure of a subsystem. Three major requirements must be considered within each method:

a. Detection time for the presence of a failure

b. Localization time for a failure

c. Restoration time for the system to achieve satisfactory performance

These requirements interface with methods for designing for reliability. Thus, the need for coordination between reliability, maintainability and system engineers.

With overall system responsibility, ESD, by scheduled monitoring visits and attendance at design reviews, can help in fostering communication between all organizations influencing system design and development.

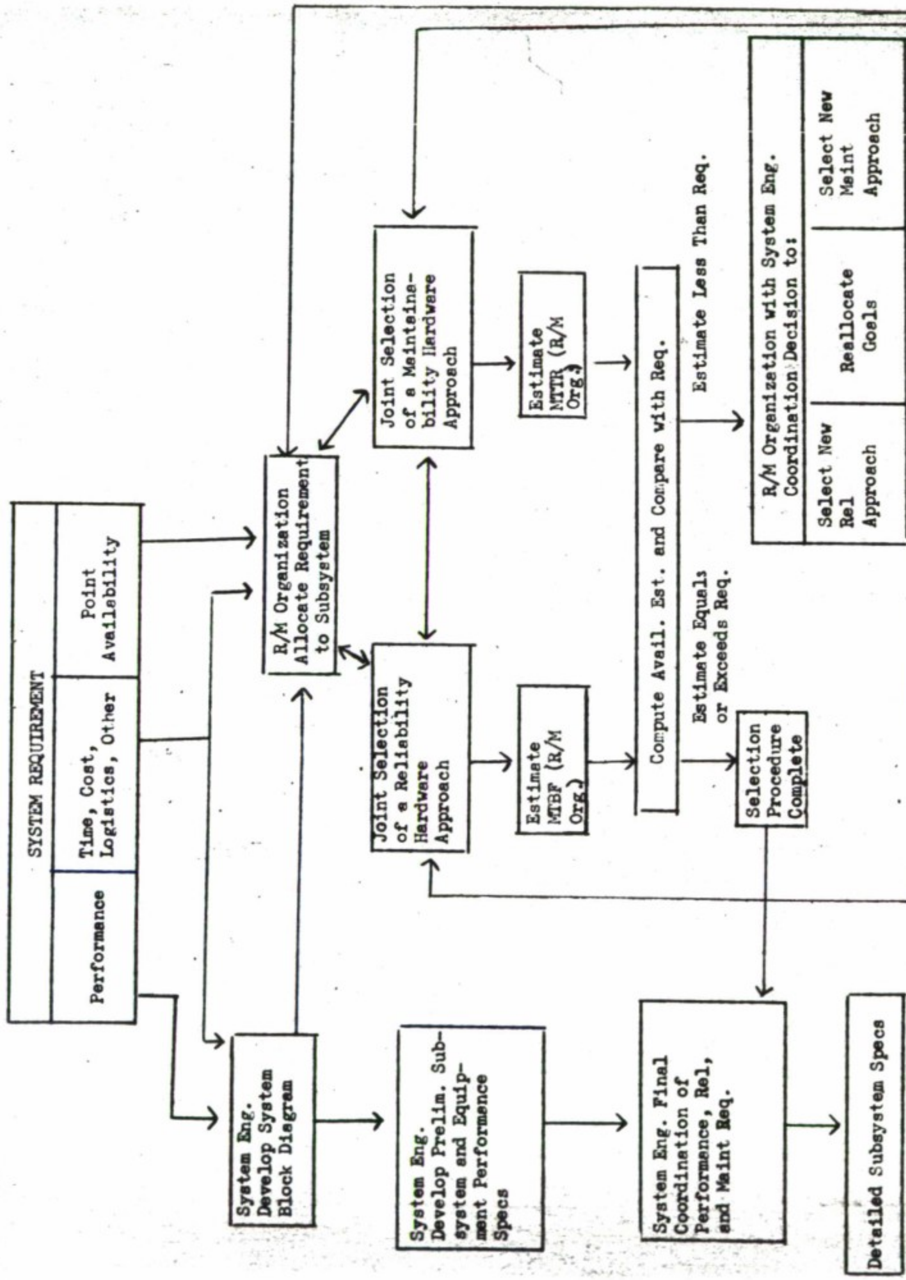

Figure 1: Systems, Reliability and Maintainability Engineering Coordination

SECTION III

GUIDANCE FOR RELIABILITY AND MAINTAINABILITY
ENGINEERS PARTICIPATING IN
CONTRACTOR DESIGN REVIEW PROCESS

SECTION III

GUIDANCE FOR RELIABILITY AND MAINTAINABILITY ENGINEERS PARTICIPATING IN CONTRACTOR DESIGN REVIEW PROCESS

FOREWORD

1. Purpose. The purposes of this section are to provide information and guidance on reliability and maintainability engineering design reviews required by MIL-R-27542 and MIL-M-26512, and to outline approaches usually taken by contractors in accomplishing such reviews.

2. To Whom It Applies. The contents of this section apply to all programs falling within the purview of ESD that will result in equipment ("hardware" as distinguished from "software") entering the Air Force inventory and where the engineering design review requirements of MIL-R-27542 and MIL-M-26512 are a specific contract requirement. ESD personnel will participate in these reviews to assure proper design consideration of equipment reliability and maintainability.

SECTION III

CONTENTS

Chapter 1

INTRODUCTION

A design review is defined as a planned continuous monitoring of a product design to assure that it meets the expressed and implied performance requirements of the equipment during operational use. Such a review provides periodic appraisal of the design effort to determine the progress being made in achieving the design objectives and systematically brings to bear specialized talent on specific problem areas. In this matter an overall evaluation is made to take into consideration specific design and interface problems that may be encountered later in the development and production cycle.

Reliability, maintainability, and value as well as other characteristics are affected by every decision the design engineer makes. This includes the choice and use of circuits and component parts, their arrangement, the environment in which the equipment will be used, to the capabilities and problems of the man who ultimately must operate the equipment under field conditions that could not have possibly been foreseen during design. Although the design engineer is not solely responsible for the operational reliability and maintainability of equipment, it is very easy to blame him when equipment has a poor reliability and maintainability field record. It should be emphasized that reliability and maintainability are not the sole responsibility of the designer, nor is designing a responsibility of the design review team and every effort should be expended to avoid such tendencies. Because of increased complexity of the equipment being designed, concurrency concepts, and new devices and techniques being employed, it is impossible for a design engineer to maintain excellence in every technical discipline affecting the design process. To obtain maturity of design necessitates evaluation by technical specialists selected for their special talents and knowledge who perform a technical analysis of the system/equipment as it pertains to their specialized fields. The design review, if properly performed, provides one of the most powerful and effective tools available to assure that reliability, maintainability, and value as well as other design characteristics have been considered early in design or at the optimum stage of development.

A purpose of an engineering design review is to analyze system/equipment requirements, electromechanical and electronic circuit design, component part applications and mechanical features, to assure essential characteristics such as reliability and maintainability at the lowest overall cost.

To achieve these ends, system program personnel will enforce and actively participate in a design review process on all programs that result in equipment entering the Air Force inventory.

Techniques for designing reliability into system/equipments usually are classified into three categories:

a. Conservative selection and application of piece parts. (See RADC Reliability Notebook)

b. Incorporation of redundant replacements and/or alternate modes of operation.

c. Minimization of environmental stresses; for example, electronic equipment must incorporate means for adequate heat rejection in order to provide reliable performance at thermal equilibrium. It cannot be over-emphasized that reliability can be obtained only if the electronic, thermal, and mechanical designs are well executed. The thermal design is fully as important as the circuit design. Ground-based electronic equipment is frequently installed in shelters having a ventilating or air conditioning system intended for the comfort of operating personnel. The cooling system for the electronic equipment must be made compatible with such a system.

A number of maintainability design techniques have been derived as possible alternative methods for restoring a system/equipment to operation subsequent to a failure. Three major requirements present in system/equipments are:

a. Methods for detection of the presence of a failure.

b. Methods for localizing a failure to a replaceable unit or assembly.

c. Methods for restoring operation after localizing the failure.

Since the majority of system/equipments under development by ESD have requirements defined in terms of statistical availability, it is necessary that design concepts which yield significant improvements in maintainability, for example, be considered for their interactions on reliability and cost.

A primary goal of a designer is to obtain an output (performance) that will satisfy a series of specific performance requirements. Additional requirements, such as reliability and maintainability, usually appear as secondary to this goal. Moreover, because a designer usually has not been sufficiently alerted to the need or logic of such requirements, he may view them as burdensome, if not irksome. Under the stress of time pressures and the complexity of the design process itself, where no one man can digest the amount of specialized technical knowledge and implications of design with the same degree of insight and understanding, reliability and maintainability requirements are most likely to be compromised.

Finally, the neglect of maintainability, serviceability, reliability, and producibility frequently means that ultimate system/equipment schedules cannot be met because of the confusion and waste caused by the multiplicity of engineering changes which result from hasty design.

Chapter 2

BASIC DESIGN REVIEW PHILOSOPHY

Design reviews begin with the conceptual phase that considers the broad general requirements and as the design approaches the hardware stage, narrows down to detailed meetings of reduced scope where only circuits, equipments, or portions of equipments are considered, and then broadens again as the various equipments are integrated into a system.

Design changes during the early-design review phases generally require very little engineering effort since it usually involves only paper changes of a part, dimension, or value, although redesign of components might at times be mandatory. Design changes occurring during subsequent design reviews involving changes to drawings, modifications, or replacement of existing hardware, replacement of field supplies, revision of field manuals, or retraining of factory and field personnel for example, will be considerably more costly (100-1000 times) although the probability of such changes will be less than during the first phase. As it pertains to reliability, maintainability, value engineering, human engineering, etc., the periodic review of design at key points in the development program facilitates detection and correction of actual or potential design problems prior to finalization of the design.

The prime purpose of a formal design review meeting must be to insure that adequate effort has been made by the designer. The design review process assures:

a. A means of solving interface problems;

b. Confidence that experienced personnel are involved in the design detail;

c. A record of why decisions were made;

d. A knowledge that systems will tie together and be compatible;

e. A total picture for the benefit and use of the final decision-maker in making trade-off decisions; and

f. A greater probability of a fully mature design.

A design review plan would include the time-phased events representing the appropriate milestones at which formal system/equipment reviews are made at major decisions points. The number of critical decision points

will vary according to the type of development program underway. The broad categories are sometimes listed as:

a. Conceptual Design Review.

b. Preliminary Design Review.

c. Preproduction Design Review.

d. Production Design Review.

These review points are keyed to major events and consequently reflect the name of that event. It is well to bear in mind the objectives of these reviews and schedule the event accordingly. The main requirements that can be applied to any program will be covered by three or four major review points, namely:

a. Conceptual Design Review.

b. Preliminary Design Review.

c. Detailed Design Review.

d. System Design Review.

Design review actions could be likened to an hour glass figure that first considers the overall concepts that narrows down as major decisions are reached to consider the electrical/functional design reviews, detailed hardware, or component reviews; then begins to broaden to combine at black box and subsystem level, and finally, an integrated system review. (See Figure 1 below.) Regardless of the names assigned the design reviews, specific milestones or decision points must be identified where formal reviews will be conducted.

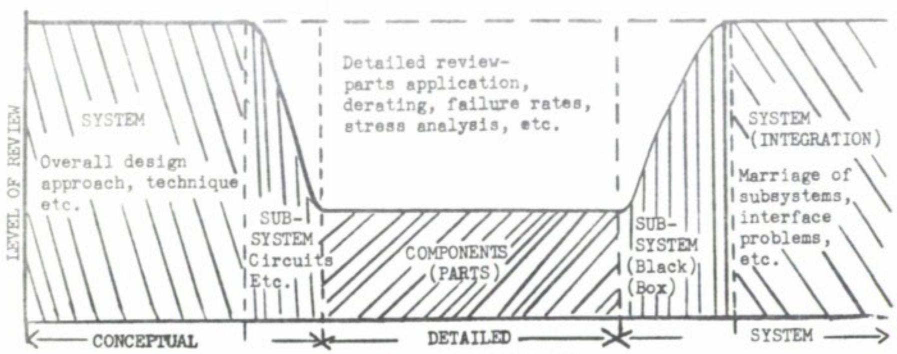

FIGURE 1. DESIGN REVIEW LEVELS

MIL-R-27542, paragraph 3.5.10, defines the requirement for contractor engineering design reviews for reliability. A similar requirement for maintainability is found in MIL-M-26512, paragraph 3.5.1.b. Both paragraphs require the submission of a schedule of planned reviews to a procuring activity and permit the attendance of procuring activity personnel at these reviews.

Since ESD policy requires the submission of a combined plan for reliability and maintainability and since system/equipment requirements are usually defined in terms of statistical availability, it is expected that separate scheduling of reliability and maintainability reviews will not be required. Further, for good systems engineering practices, system/equipment reliability/maintainability engineering reviews can be integrated within the general framework of the requirements of AFR 80-28, Engineering Inspections. However, there still remains the need for the depth of inquiry into reliability and maintainability engineering design practices as illustrated by the Design Review Check List (see attachment 1).

Chapter 3

CONTRACTOR DESIGN REVIEW BOARDS IN GENERAL

The review and approval of proposed contractor Design Review Plans by a procuring activity should include the detailed examination of the general management policy statement that officially delegates clear task charters to organizational groups. It should be verified that necessary action has been taken to assure the design review functions are manned, formats and instructions are developed and distributed, and training seminars completed where required.

The organization to which the responsibility for design reviews is assigned will vary according to the company involved. However, the organizational assignment is not nearly so important as the authority delegated to this Board and the support given this important function by high level management. In most companies, the function falls within the Engineering Division, while in some the Board is Chaired by the Reliability Department. In any case, the ultimate responsibility for a design must rest with a design engineer, but top management support is essential for the program to succeed. If sound recommendations for design improvement are ignored, the program is doomed. Although it may seldom be necessary, engineers assigned to design reviews should know that they can appeal to higher management.

A Design Review Board performing design reviews may be composed of permanent members augmented by experienced talent in the various technical areas. A Design Review Board should have one or more senior design engineer(s), project engineer, reliability engineer, maintainability engineer, and value engineer that would form a permanent framework, with other specialists being made available as the requirement arises. Some companies estimate that an effective Board should be limited to ten members. This will vary depending upon the type of review being performed and the equipment involved. The disciplines requiring coverage during the reviews are reliability, maintainability, human factors, value engineering, design engineering, manufacturing, logistics, etc. The technical ability of personnel required to participate in these reviews will vary according to the complexity of the system.

However, conceptual and system design reviews should be performed by experienced, senior engineers. Detailed equipment design reviews should be performed by engineers more closely associated with circuit design, parts application, etc. Again, the actual number of personnel participating in formal design reviews should be kept to a minimum commensurate with the specialists required for the problems to be considered. When such specialists as metalurgists or comparable authority are required, they should be schedulsd to join the group at a specific time and then be dismissed as soon as possible.

ESD must be alert to contractor methods of budgeting for scheduled design reviews to assure that costs are not compounded by each department participating in reviews. Design review costs will normally be proportional to the complexity of the equipment which dictates the number of reviews required as well as the number of personnel attending. It is important to stress that ESD considers design reviews, although they may appear costly, as the most effective means of assuring that the Air Force gets a full measure of maturity in all aspects of design. A rule-of-thumb figure sometimes applied is that design reviews require 5% of the overall design-manhours.

Design review milestones should be identified early in the program and will normally be coincident with the main development phases such as conceptual, breadboard stage, pre-prototype, prototype, preproduction, etc. (see Chapter 2). The review points identified should be firmed up approximately 30 days in advance of a formal design review and data packages should be distributed to all attendees along with formal notification ten days prior to actual date a review is to be held. The MIL-R-27542 requires the contractor to notify the AF procuring agency ten days in advance of a meeting so they may participate if they so desire. In any case, the minutes, agenda, actions, and documentation should be available for review when requested by the procuring agency.

Specific information that must be reviewed and monitored by ESD during a contractor design review program includes:

a. Personnel (their experience levels) assigned to the program.

b. Organizational assignments, modus operandi, authority delegated to the Design Review Board.

c. Design handbooks and check lists prepared for design engineering use.

d. Design review plan--milestone identification, etc.

e. Data packages developed for design review use. These packages should include, as required, worst case studies, circuit analysis, parts application data, drawings, etc. The completeness of packages is very important for individual use in preparation for design reviews.

f. Recorded actions by a Board including rejected recommendations with reasons for rejection.

g. Approved design changes and their documentation.

h. Records indicating problem areas not resolved at the meeting with action assignments for resolution, specific problems to be studied,

target dates for completion, and methods of follow-up to assure completed actions.

i. Final approval of design by respective specialists by affixing signature on Board minutes.

Chapter 4

CONCEPTUAL DESIGN REVIEW

The conceptual design review is the most important design review to be accomplished. Important decisions are made at this time that preclude or freeze subsequent designs. It is therefore logical that this review should be attended by the largest group of knowledgeable engineers. This Design Review Board must consider the feasibility of design; the techniques to be employed in achieving performance requirements; the interface problems which involve system, maintenance, and design concepts; and specific design requirements that might conceivably push the state-of-the-art. Major design characteristics such as performance, reliability, maintainability, and value must be carefully considered. A proposed configuration should be reviewed for such considerations as the use of standard circuits of proven reliability, comparison of one computer manufacturer with another, evaluation of belt-drive versus direct-drive, the need for redundant replacements, the hardware approach to be followed in the identification and localization of system failures, methods to minimize the influence of limited or critical life items on the operational capability of the system/equipment, etc. With such considerations a paper study may be accomplished to obtain an estimate of the system's reliability, maintainability, or other figures of merit. This study is then available as a valuable tool to assist the Board in selecting the ultimate system configuration. Although early reviews cannot be rigorous in design detail, the early design decisions are extremely important for these decisions commit the program to a specific design approach or strategy. Improper logic or design approaches should be ferreted out at this point while changes involve only paper changes and before actual equipments begin to take shape. As the design progresses, subsequent changes become much more expensive and tedious to accomplish (see Chapter 2).

The material or data that should be available for use by the Board in its preparation and deliberation includes:

a. The proposal;

b. The Specific Operational Requirement (SOR);

c. The Statement of Work and associated specifications;

d. The analysis of system requirements;

e. Basic design criteria (block or logic diagrams and flow charts);

f. Reliability and maintainability requirements;

g. Possible trade-off documentation; and

h. System/equipment schedules with milestones.

An important outcome of conceptual or system design reviews is the ability of the systems contractor to quantify reliability and maintainability requirements at the subsystem level for the guidance of design engineering personnel and for insertion into subcontracted equipment specifications.

Subsystems and component detail design reviews are concerned with determining the maintainability and reliability characteristics of subsystems during the detail design phase of program development. The purposes of this effort, described in Chapter 5, are to determine the extent to which the various designs in process will achieve the requirements set forth as the result of the conceptual or system design review and to indicate the need for redistribution of system requirements.

Chapter 5

DETAILED SUBSYSTEM DESIGN REVIEWS

The number of formal, detailed subsystem design reviews scheduled and the optimum time for reviews will vary as a function of the system complexity, the type of equipment being utilized, the caliber of cognizant design engineers, etc. However, formal design reviews should be conducted prior to release of any design to production. At major review points every facet of the design considerations should be carefully gone over. A design review check list should be utilized to assure consideration of all important criteria (see attachment 1). A check list may by necessity be tailored to fit the specific requirements of a system, but in any case it should not be a different set of criteria from the ones used by designers. It would be unreasonable to confront the designer with a new set of rules at the time of review.

A design handbook should be prepared to reflect the specific requirements of the project and made available to design engineers. These design handbooks should be reviewed for adequacy of content and acceptability to ESD programs prior to commencing the design effort. ESD does not presume to dictate the manner in which a design review will be conducted, but aims to evaluate that effort and to take appropriate action when review actions fail to satisfy the design review purpose as related to scope, depth of analysis, corrective actions taken, or experience of participating members.

Development Engineering personnel of the Contract Management Regions should be fully utilized to provide continuous surveillance of the design review effort. This source of engineering talent is important to the SPO effort and should not be overlooked--their contribution will be of great value to the overall effort.

Design reviews should not be staged affairs that reflect the results of previous meetings, but should indicate a thorough preparation and attention to detail by all participants. The design engineer should be prepared to defend all decisions reached by him by presenting required studies (including breadboard test data, if available), and engineering calculations. He should be prepared to defend the selection of a resistor, for example, not by merely stating that it is reliable, but by saying this resistor was chosen because it is a standard item with the lowest possible cost to perform the required function; it is derated to 25% of its normal rating for the following reasons ... ; it is considered as reliable as any item available based on the present state-of-the-art and is expected to give a long trouble-free life or MTBF of X hours.

Engineers attending reviews should be thorough in their pre-review analysis of what they consider as potential problem areas and should be prepared to indicate in detail what the effects of their recommended changes will have upon the major characteristics of the equipment. It is also important that Board members notify the designer of areas of disagreement in sufficient time before the formal meeting to allow him to assemble reference material to support his decisions, thus allowing the Review Board to thoroughly consider both sides of the question. The complete analysis and presentation of facts rather than theories enables sound decisions to be reached in the shortest period of time. Examples of the types of data necessary to facilitate detailed reviews include:

a. System reliability predictions.

b. Detailed subsystem, circuit reliability predictions.

c. Maintainability predictions, studies, and task simulation results.

d. Component parts lists with appropriate test information.

e. Parts derating and application data.

f. Parts failure rate data (or sources).

g. Stress analysis results.

h. Failure effects analysis.

i. Statistical analysis of circuit (or assembly) performance as a function of parts variability. Error and tolerance studies.

j. Reliability aspect of redundant parts, assemblies, subsystems, modes of operation with attention to switching problems.

k. Consideration of potential reliability growth.

l. Documented reliability growth plans.

m. Analyses of known trouble areas, with plans for corrective action.

n. Technical data, including equipment physical construction and profiles, block diagrams, schematics, signal flow charts, equipment operating theory, maintenance philosophy, operating procedures and maintenance instructions.

The maintainability portion of design reviews are concerned with such equipment or design features as:

a. Packaging - Is equipment of modular construction for easy unit replacement?

b. Labeling - Are parts and controls clearly and accurately labeled?

c. Protective devices for components and circuits.

d. Quick-release features of connectors, latches, and fasteners.

e. Availability and access of test points.

f. Self-test features or built-in test equipment. Operation and fault detection features.

g. Adjustments - Are required adjustments kept to a minimum?

While the above design features are important for the achievement of quantitative parameters, it is recognized that maintainability improvement is not limited to equipment changes, but can be produced by providing proper diagnostic routines and maintenance aids which increase relative ease and simplicity of performing maintenance tasks, changes in operating, test or maintenance procedures, and insuring the efficient selection and utilization of tools, test equipment and maintenance personnel. Inherent maintainability or repairability is a design feature which can be controlled during the design process, but the achievement of satisfactory operational maintainability requires a consideration of a wider spectrum of activities than the design process itself.

As the design process progresses to the stage where mock-ups are available, an efficient and excellent design review tool is available to a Design Review Board. The maintainability engineer can make maximum use of mock-ups in visualizing access requirements, resolving space conflicts, etc. The ability to visualize a problem in a realistic three dimensional environment can serve to expedite the arrival at satisfactory solutions to problems. Where problems arise that involve making trade-offs, the mock-up should enable personnel working on problems to visualize various alternative solutions before drawing board time is expanded. Unsatisfactory trade-offs can be discarded before any appreciable expense has been incurred in exploring them.

An important inherent consideration of the engineering design review process is the identification of preventive and/or corrective maintenance tasks which require actual demonstration. Task demonstration requirements will most frequently be generated as a result of one or more of the following considerations:

a. Tasks are highly critical in terms of system/equipment operability.

b. Tasks are unique, exceedingly exacting and/or new or complex.

c. Tasks are associated with potentially hazardous environments and/or equipments and adequacy of safety procedures and devices needs to be verified by simulation before actual task performance can safely be permitted.

The selection of tasks in turn requires that a demonstration procedure be established for each task. The procedure must specify precisely what is to be done, the tools, equipment and personnel to be employed in performing the task, the environment and equipment configuration to exist during the demonstration and an explanation of exactly what specific information is expected to be obtained. The results of task demonstrations should become a part of the technical data available to a Design Review Board. Simulation results may uncover features of equipment design requiring corrective action.

Finally, while the discussion has been on formal Design Review Board actions, ESD should take a more general look at the interaction of a contractor's reliability/maintainability and design organizations during program monitoring. The influence of the reliability/maintainability organization on the design process must not be felt only at formal Board meetings. A continuous interaction on questions of design strategy should take place between these organizations throughout the design process.

Chapter 6

DESIGN REVIEW CHECK LIST

The design process itself and subsequent reviews should never be left to chance, but should always be conducted according to a systematic plan. To assure that important design considerations have been considered by designer and reviewer, a comprehensive check list should be employed.

An example of a list developed by Radio Corporation of America (RCA) is presented for general guidance in Attachment 1. The material in the check list presents a formidable array of questions which have been found necessary for an adequate evaluation of system/equipment characteristics.

While the check list serves as a design, it is important to recall that design guidelines are available in numerous publications by Government agencies; for example, the RADC Reliability Notebook contains a family of interaction models which relate, for various part classes, part operating stresses and failure rates and can be applied by a designer in arriving at satisfactory component part derating procedures (subject to the constraints of size, weight, and cost).

ESD personnel attending formal design review meetings are also urged to become familiar with the design techniques described in various AFSC manuals to assist in their evaluation of proposed designs. Several methods of circuit analysis for reliability purposes are described in Attachment 2.

DESIGN REVIEW CHECK LIST

PART I - ELECTRICAL

1. Parts Selection and Evaluation

   a. Have the appropriate standards been consulted for selection of standard electrical components?

   b. Can a redesign omit a nonstandard part or replace it with a standard part?

   c. What parts are nonstandard?

   d. Hava raquests been initiated for approval of nonstandard parts?

   e. Have environmental tests been started on nonstandard parts?

   f. Have potted circuits been subjected to environmental testing?

   g. What are the parts having the highest failure rates?

2. Parts Application

   a. Resistors

      (1) What is the operating ambient temperature?

      (2) What power dissipation is estimated in this application?

      (3) Is the resistor properly deratad?

      (4) What tolerance limit is required for satisfactory circuit operation?

      (5) What tolerance buildup (due to temperature, aging, electrical strass, etc.) can be allowed?

      (6) Has the rated wattage been adjustad in cases where short mounting leads are used?

      (7) Can any potentiometers be replacad by resistors?

      (8) Has the voltage limit been excaedad on any fixed composition resistors?

   b. Capacitors

      (1) What is the operating ambient temperature?

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(2) What is the working voltage expected in this application?

(3) Is the capacitor properly darated?

(4) Is the capacitor subject to surge voltages which exceed the rated operating voltage?

(5) What tolerance limit is required for satisfactory circuit operation?

(6) What tolerance buildup can be allowed?

(7) What derating factor was used for a-c ripple or pulse voltages on MIL-E-25A paper capacitors?

(8) Have capacitors with adequate temperature ratings been used wherever possible?

(9) Have temperature-compensating or low temperature coefficient capacitors (mica or ceramic) been used wherever high stability is required?

(10) Have high dielectric ceramic capacitors been restricted to bypass usage?

(11) Are tantalum capacitors bypassed for high frequencies (above 100 kc)?

(12) Are all capacitors heavier than 0.5 oz. securely mounted in accordance with specification MIL-E-5400, para. 3.1.3.5?

c. Tubes

(1) Does the specification of the tube type selected define the required characteristics?

(2) Does the operation of the tube approach any absolute rating under any usual variation of supply voltage or load?

(3) What is the operating ambient temperature?

(4) What electrode ratings are of critical consideration in this circuit application?

(5) Is the heater voltage within rating? What variations are expected?

(6) Is the heater-to-cathode voltage within rating in this circuit application?

(7) Are the plate and screen grids properly derated?

(8) What tolerance buildup can be allowed?

(9) Has Gm variation been considered?

(10) Were maximum grid resistance ratings observed?

(11) Is input and/or output capacity a critical consideration in this circuit application? What variation in input and/or output capacity can be tolerated?

(12) Does circuit operation depend upon a tube parameter not controllable by the designer?

(13) What is the maximum rated vs. maximum expected bulb temperature?

(14) Will the circuit perform satisfactorily with randomly selected tubes? - with tubes operating at their upper or lower MIL limits?

(15) Has tube approval date been taken?

(16) If a printed-circuit board is being used, have adequate cooling measures (convection to cooling air or conduction to a heat sink) been taken to prevent damage to the board or components mounted on it?

(17) Have standard tube shields been used?

d. Transistors

(1) Does the specification of the type of transistor selected define the required characteristics?

(2) Does the operation of the transistor approach any absolute rating under any usual variation of supply voltage or load?

(3) What is the operating ambient temperature?

(4) What is the maximum rated power dissipation? What is the maximum power dissipation expected in this circuit application?

(5) What is the maximum rated collector voltage? What is the maximum collector voltage in the present application?

(6) What is the maximum rated collector current?

(7) What deviation in Beta is tolerable?

(8) How much deviation in Beta is expected due to tolerance buildups?

(9) Will the circuit perform satisfactorily with randomly selected transistors? - with transistors operating at their upper or lower MIL limits?

(10) Is power gain a critical consideration in this application?

(11) What deviation in power gain is tolerable?

(12) What deviation in power gain is expected due to tolerance buildup?

(13) Is noise figure a critical consideration in this application?

(14) Is the noise figure tolerable at the operating ambient temperature?

(15) How much leakage current is expected at the operating ambient temperature?

e. Semiconductor Diodes

(1) Does the specification for the type of diode selected define the required characteristics?

(2) What is the operating ambient temperature for each diode?

(3) What is the power dissipation within the diode? What is the maximum rated power dissipation?

(4) How much reverse recovery time does the diode require?

(5) What is the rated peak inverse voltage?

(6) How much reverse current can be tolerated?

(7) How much reverse current will flow at the operating ambient temperature?

(8) Does the circuit perform satisfactorily with randomly selected diodes? - with diodes operating at their upper or lower MIL limits?

(9) What Zener voltage reference is required? What Zener reference voltage is expected?

f. Transformers, Chokes and Coils

(1) What is the operating ambient temperature?

(2) Is Q a critical consideration in this circuit application? What deviation in Q can be tolerated?

(3) What deviation in Q is expected due to tolerance buildup and to temperature changes?

(4) What is the maximum current carrying capability of the choke or coil? What is the maximum current expected in this application?

(5) How close is the highest operating frequency to the resonant frequency of the choke or coil?

(6) Has a requirement for shielding been established?

(7) When a hum problem exists, has special consideration been given to core construction?

(8) Do transformer specifications conform to MIL standards?

g. Relays and Switches

(1) What "quality level" does each relay or switch represent?

(2) How many actuations per hour are expected?

(3) How many actuations per mission are expected?

(4) What percent of rated current does each contact carry?

(5) Is relay closing time or opening time a critical consideration? If so, how much increase is tolerable?

(6) What are the pull-in and dropout voltages or currents?

(7) What is the manufacturer's tolerance for initial coil resistance.

(8) How much will the coil resistance vary with temperature?

(9) How much change in coil resistance is tolerable?

(10) Has arc suppression been used?

(11) Has the possibility of dry circuit operation been considered?

h. Electromechanical Devices

(1) Have the adverse affects on brushes at high altitudes been considered?

(2) What consideration has been given to variations of d-c motor speed-torque characteristics due to temperature and altitude?

(3) How critical to proper operation is the speed-torque characteristic?

(4) Can the associated circuitry tolerate increased loads caused by variation in motor characteristic?

(5) Have the appropriate specialists been consulted on the use of rotary solenoids and timing motors?

(6) Have you depended solely on manufacturer's data for force-movement characteristics of solenoids?

(7) Are meter windows sealed to prevent moisture formation?

(8) Has the possibility of charge formation on meter windows been investigated?

(9) Are resolvers checked for accuracy and phase shift at elevated temperatures?

i. Connectors and Plugs

(1) Does the number of active pins per connector conform to the recommended limit?

(2) Is a sufficient number of spare pins available on each connector? (At least four spares for connectors over 26 pins per MIL-E-5400C, paragraph 3.1.5.3.)

j. Miscellaneous Parts (Printed Circuits, Wire, etc.)

(1) Has consideration been given to the current rating of wire?

(2) Has the current rating of wire been reduced in cases where voltage drop is important?

(3) Is wire color coding required, and, if so, is it in accordance with the proper standards or specifications?

(4) Has the placement of components on printed-circuit boards been considered from the cross-talk point of view?

(5) Does a heat dissipation problem exist on printed-circuit boards?

(6) Is a keying scheme employed to prevent interchanging printed-circuit boards?

(7) Are transistor, diode, and tantalytic capacitors properly polarized on printed-circuit boards?

(8) Are large potential gradients possible between adjacent pins or connectors on printed-circuit boards?

(9) Do circuit breakers conform to MIL-C-5989B?

3. System and Circuit Considerations

(1) What variations in input signal can be tolerated? What variations are expected?

(2) What variations in the impedance presented to the input terminals can be tolerated? What is expected?

(3) How does the input circuitry contribute to input tolerances?

(4) Is a-c power supply distortion a critical consideration?

(5) What percentage of distortion can be tolerated? What is expected?

(6) What tests have been performed to confirm the answers to questions in Para. (5) above?

(7) What variation in B+ voltage(s) can be tolerated?

(8) What variation in bias voltage can be tolerated?

(9) What design features protect the circuit against excessive variations in line voltage?

(10) Whet design features protect the circuit against loss of B+ or bias voltage applies?

(11) What cable length was assumed on inputs and outputs?

(12) How much change in the assumed cable length can be tolerated?

(13) Is over-sll protection provided against overload, excessive heating, pressure changes, etc?

(14) Do the self-test features of the unit meet the requirements?

(15) What problems were observed when the circuit was tested in conjunction with other units?

(16) Has the unit been subjected to environmental testing? What problems were observed with respect to temperature, moisture, vibration, shock, altitude?

(17) Have all problems highlighted in the preliminary design review been resolved?

(18) Has a seperate list of recommendations for product improvement or redesign been compiled?

(19) What alternate circuits or systems were considered?

(20) Have "preferred circuits" been used wherever possible?

(21) What factors influenced the choice of tbis particular circuit or system?

(22) Are there firm specifications for this circuit, including test specifications?

(23) Have all specifications been met unconditionally?

(24) Does any specification require modification.

(25) Can any unreasonable or unusually difficult requirement be relaxed?

(26) Can a simulation study be of assistance?

(27) What marginal testing has been performed? Wes marginal operation indicated in any case? What are tbe critical parameters affecting marginal operetion?

(28) Have heat runs been made on electrical components which are either thermal emitters or otherwiee heat sensitive?

(29) Have phase margin checks been performed on all feedback loops?

(30) What decoupling or neutralization echemes have been implemented to avoid regenerative feedback loops?

(31) What analyses have been performed to determine the existence of feedback loops and their effects on other circuits?

(32) Is circuit operation contingent upon the proper positioning of more than one switch or control; i.e., are several adjustable components necessary in the circuit?

(33) Can any circuits be simplified and still operate within requirements? (On a value improvement basis)

(34) Is the unit capable of satisfactory operation after tbe minimum required warm-up time?

(35) What system adjustments are required when a unit is replaced?

(36) What means are employed to decouple the power supply?

(37) Do parasitic oscillations exist?

(38) What design features have been incorporated to suppresa parasitic oscillations?

(39) What are the required tolerances on output signals? What are the expected variations?

(40) How does the circuitry contribute to output tolerances?

(41) Do weight reduction considerations affect reliability?

(42) Have static and dynamic power drains been determined?

4. <u>Reliability Analysis</u>

(1) What is the estimated required mean life of this circuit?

(2) What is the calculated mean life?

(3) What is the mean life, based on bench or other teete?

(4) Is there a history or record of bench failuree?

(5) Have random failure rates and wearout rates been established for all parts?

(6) What parts have an excessive failure rate?

(7) What assumptions were made in calculations with respect to derating and temperature?

(8) Are any parts operating near or above their recommended ratings?

(9) Has a statistical analysis been conducted to determine effects of drift in component parameters and of component tolerance buildups?

(10) Has a fail-safe design philosophy been utilized?

(11) Is protection against secondary failures (resulting from primary failures) incorporated where possible?

5. Safety Factors

(1) Is there adequate protection against dangerous voltages?

(2) Are high-voltage warning plates necessary?

(3) Have interlocks, safety switches and grounding bars been considered?

(4) Are all external metal parts at ground potential?

(5) Are discharging rods necessary for large capacitors? (at least 10,000 ohms)

(6) Are bleeder and current limiting resistors used in power supplies?

(7) Are there burning hazards?

(8) Are "hot" terminals exposed when plugs or connectors are not connected?

(9) Are adjacent plugs or connectors keyed to prevent interchanging connections?

(10) Can maintenance or adjustment be performed safely?

6. Maintenance

(1) Are the maintenance and test equipment requirements compatible with the concept established for the system?

(2) Does the unit require special handling?

(3) Can the unit be readily installed and connected to the system?

(4) Are factory adjustments such that they do not require readjustment when units are replaced in a system or when parts are replaced in the unit in the field?

(5) What adjustments are necessary after a unit has been installed in the system?

(6) Are adjustments capable of compensating for all possible tolerance buildups?

(7) Is periodic alignment and/or adjustment recommended? How often?

(8) Are all requirements for maintenance tests such that the specified time limitations can be met?

(9) Has the number of factory adjustments been minimized?

(10) Has the number of field adjustments been minimized?

(11) Are interconnected circuits in the same package, thus providing minimal inputs and outputs at each maintenance level?

(12) Is the interaction between adjustments and other circuit parameters minimized?

(13) Is the design such that damage to the circuit cannot result from careless use of an adjustment or combination of adjustments?

(14) Are all adjustments and indicators of the "center zero" type where possible?

(15) Is periodic testing necessary? How often?

(16) Are the test points adequate? Are they accessible in the installed condition?

(17) What overhaul testing is required?

(18) What specific test equipment is necessary?

(19) Have factory and maintenance teet equipment requirements been minimized and coordinated with the requirements for other units?

(20) What special techniques ere required in the repair, replacement, or alignment of the unit?

(21) Are parts, assemblies, and components pleced so there is sufficient space to use test probes, soldering iron, and other tools without difficulty? Are they placed so that structural members of units do not prevent access to them?

(22) Are testing, alignment and repair procedures such thet a minimum of knowledge is required on the part of maintenance personnel? Can trouble shooting of an assembly teke place without removing it from e major component?

(23) What special tools and/or test equipment are required?

(24) Can every fault (degrading or catastrophic) which cen possibly occur in the unit be detected by the use of the proposed test equipment and standerd teet procedures?

(25) Heve parts subject to early weerout been identified? Have suitable preventive meintenence schedules been established to control these parts?

(26) Are the components having the highest failure rates reedily accessible for replecement?

(27) Are parts mounted directly on the mounting structure rether then being stacked one on another?

(28) Are units and essemblies mounted eo thet replecement of one does not require removel of others?

(29) Are limiting resistors used in teat point circuitry; i.e., is any component likely to fail if a test point is grounded?

(30) Can panel lights be easily replaced? (Panel lights should not be wired in series)

(31) Have voltage dividers been provided for test points for circuits carrying more than 300 volte?

(32) Will the circuit tolerete the uae of a jumper ceble during maintenance?

(33) Are controla loceted where they cen be eeen and opereted without disassembly or removal of any part of the installation?

(34) Are releted displays and controle on the eame fece of the equipment?

(35) Are all units (and parte, if poasible) labeled with full identifying data? Are parts atamped with relevent electricel characteristics information?

(36) Are cables long enough to permit each functioning unit to be checked in a convenient place?

(37) Are plugs and receptecles used for connecting cebles to equipment units, rether than "pigtailing" to terminel blocks?

(38) Are field-replaceeble modules, parts and subessemblies plug-in rethar then soldered?

(39) Are cable harnessea designed for fabrication es a unit in a shop?

(40) Are cebles routed to preclude pinching by doors, covers, etc?

(41) Is eech pin on each plug identified?

(42) Are plugs designed to preclude insertion in the wrong receptable? Are plug-in boarda keyed to prevent improper ineertion?

7. Electrical Interference

(1) Do all the provisions of specification MIL-I-26600 epply, or should some waivers be sought?

(2) What tests have been performed for electricel noise?

(3) Has the chassis or frame been grounded? Have shock mounts been bypassed with ground streps? Hes the insuleted protective finiah been removed where a metal-to-metel contact is required?

(4) Are openings (such as those for access, ventiletion, and cese-mounted components) shielded to prevent cese leakage? Are access doors of the metel textile or finger atrip type?

(5) Are heeters wired with twisted or isolated leade?

(6) Are oscillators isolated from other stages and from antennas? Is oscillator power kept to a minimum? Is the oscillator heater decoupled from B supply sources?

(7) Do parasitic oscillations exist, and is suppression necessary?

(8) Is undesired signal transfer reduced by means of interstage decoupling networks and link or parallel-tuned circuits?

(9) Are pulse networks and transformers isolated? Are the leads associated with the pulse networks decoupled? Are these leads kept as short as possible?

(10) Is pulse energy fed to succeeding stages in coaxial leads where possible? (Guard against waveform distortion caused by coaxial cable capacitance.)

(11) Are sharp projections avoided in high-voltage circuits? (They are possible sources of corona and arcing.)

(12) Are sharp bends avoided in high-voltage wiring? (The possibility of insulation breakdown is increased.)

(13) Are the magnetic fields associated with indicators adequately isolated? Are indicator control and power leads decoupled by the use of feed-through bypass capacitors?

(14) Are blower motors of the a-c noncommutating type?

(15) If it is necessary to use d-c rotating electrical equipment, is the design such as to minimize the effects of the commutation process? To this end, does the equipment employ such devices as interpoles, laminated brushes, as large a number of armature coils and commutator bars as possible, and good mechanical design and construction?

(16) Is relay or switch operation likely to create power supply transients in other units or circuits?

(17) Has consideration been given to arc suppression during the making or breaking of switches or contacts? (Several methods are available, e.g., a simple RC network across the switch or contacts, a high resistance or rectifier across the inductive circuit, negative voltage characteristics resistors. If these are inadequate, shielding and feed-through capacitors in the input and output leads may be required.)

(18) Are gas tube heater supplies and output leads well decoupled and isolated?

(19) In power supplies using gas-tube rectifiers, is use made of line filters, electrostatically shielded transformers, and hash-suppression chokes in the plate and cathode leads?

(20) Are electronically regulated power supplies provided with decoupling circuits to prevent oscillations in the regulator? Are long leads avoided in the plate and grid circuits?

PART II - MECHANICAL

1. General Design

(1) Has use of cantilever mounting for parts and assemblies been minimized, and, where used, is the center of gravity located near the mounting?

(2) Has the chassis been properly designed for its application?

(3) What are the locations and load ratings of mounting points?

(4) Where are the heaviest parts located?

(5) Are all large parts and assemblies securely mounted?

(6) Has the center of gravity been considered in terms of the proper distribution of shock mounts?

(7) In the case of terminal boards, are the critical components mounted at the edges rather than at the center, and are they properly supported?

(8) In the case of lead-mounted parts, have weight, lead weight, thermal expansion, supplementary support, bend rate, and other mounting considerations been evaluated?

(9) Have clearances been provided with due consideration for vibration, shock and noise stresses?

(10) Can electrical instability be caused by vibration of mechanical parts?

(11) Have shock and vibration tests been performed? If not, are they scheduled?

(12) Has the cooling design been analyzed to provide a temperature contour?

(13) Are heat dissipating elements properly located with respect to heat sensitive parts? Is there suitable flow of air?

(14) Have component parts, subassemblies and assemblies been supported and clamped properly with adequate consideration for heat dissipation?

(15) Is the unit of the lightest weight consistant with sturdiness, safety and reliability?

(16) Are all items visually and physically accessible when the unit is on the test stand?

(17) Is the possibility of physical damage to the unit due to misuse of adjustments minimized by the design?

(18) Is the possibility of damage to the unit during handling and installation minimized by the design?

(19) Can the unit be removed and replaced within the required time limit?

(20) Is the packaging scheme such as not to impose unrealistic spare parts requirements?

(21) Does each part of the unit designed as non-field repairable meet the minimum reliability requirement for this classification?

(22) Have suitable heat treatments been called out?

(23) Has design been based on standard tooling wherever possible?

(24) Have radii, fillets, curves, and straight lines been sufficient to give all possible freedom to manufacturing?

(25) Have the most economical parts satisfactory for the application been specified in all cases?

(26) Are all purchased components called out by MIL, AN or RCA (not vendor) numbers?

(27) Are the components arranged and mounted for the most economical assembly and wiring?

(28) Are all fasteners large enough for their application?

(29) Are guide pins, keys and latches of sufficient strength?

(30) Is the basic structure of sufficient strength for the application?

(31) Is the design such as to prevent excessive radiation into or out of the unit?

(32) Are parts located to provide for logical wiring?

(33) Are lubrication points minimized? Where required, are they accessible and clearly marked?

(34) Is the predicted reliability within the unit requirement?

(35) Have unit environmental tests, including temperature measurements at key points, been completed? If not, are they scheduled?

(36) Have all problems highlighted in the preliminary design review been resolved?

(37) Has there been compiled a separate list of recommendations for product improvement or redesign?

(38) What alternate designs were considered?

(39) Have the appropriate standards been consulted for materials, components, drafting, manufacturing and workmanship?

(40) What factors influenced the choice of this particular design?

(41) Do firm specifications exist, including test specifications?

(42) Have all specifications been met unconditionally?

(43) Does any specification require modification?

(44) Can any unreasonable or unusually difficult requirements be relaxed?

2. Workmanship and Maintainability

(1) Is soldering adequately specified? What provisions have been made to prevent cold joints and to ensure removal of flux?

(2) Are proper screw lengths and locking provisions specified?

(3) Are designs such as to prevent damage to components during installation?

(4) Have guide pins been provided to facilitate installation of plug-in units?

(5) Are plug-in units keyed (by some means other than the connector) to prevent accidental insertion in the wrong location?

(6) Have tolerances of component mounting provisions and mating holes been coordinated?

(7) Have all holes been located far enough from bends to prevent distortion?

(8) Are bend radii specified to be large enough, in accordance with appropriate standards?

(9) In reference to wiring and cabling, have the following items been considered?

a. Does the design make provision for properly leading cables around corners and sharp edges?

b. Are grommets provided where needed?

c. Is the design such as to minimize soldering iron burns during both manufacture and maintenance?

d. Is lacing properly and adequately specified?

e. Have harnesses been properly routed and has sufficient clamping been provided to prevent cables hanging loose?

f. Has adequate space been allowed for harnesses and for breakouts to connectors, etc?

g. Are heavy wires being brought to terminals of adequate size?

h. Are stranded wires properly secured close to solder joints to prevent flexing?

i. Is any cable (or wire) overly taut, with strain being placed on the connector (or connection), the cable (or wire) or the clamps?

j. Do any cables or wires lie across removable units or across fasteners of any type?

k. Are all connectors visible, and are they easily accessible to tools and hands?

l. Have cables (wires) and connectors (connections) been properly identified? Can wrong connections result from cable layout and connector type?

m. Do any cable (wire) runs permit contact between the cable (wire) and moving parts?

(10) Are all items (parts and subassemblies) visually and physically accessible for assembly, wiring rework and maintenance?

(11) Are all test points accessible when the unit is properly installed?

(12) Are all field adjustments accessible when the unit is properly installed?

(13) Has sequential assembly been avoided which results in involved sequential disassembly in order to make repairs and adjustments?

(14) Is the design such that no unrealistic requirements for special facilities for maintenance, storage or shipment are imposed?

(15) Is the design such that no unnecessary requirements for a special maintenance environment (e.g., ground power carts, cooling, special primary power, etc.) are imposed?

(16) Does the design provide for adequate protection of maintenance and test personnel against accidental injury?

3. Materials and Processes

(1) Have standard materials been specified in all possible cases?

(2) Have the most economical materials and processes suitable for the applications been specified in all cases? (Material cost, fabrication cost and finishing cost should be considered.)

(3) Have corrosion-resistant materials or finishes been provided?

(4) Are there dissimilar metals in contact?

(5) Are all materials satisfactory for the temperatures involved?

(6) Is the possibility of flaking considered?

(7) Has moisture protection been provided where necessary?

(8) Are all materials fungus resistant or inert?

(9) Are electrically conductive finishes provided where necessary?

(10) Have machine finishes been reviewed for the most economical processes suitable for the requirements?

(11) Have rivets or spot welds been specified where possible in preference to welding, furnace brazing, etc?

(12) Has each sheet metal piece been examined to determine whether it has too many bends for economical fabrication?

PART III - HUMAN ENGINEERING

(1) Are visual indicators mounted so that operator can see scales, indices, pointers or numbers clearly? Are scale graduations, design of numerals and pointers, and scale progressions presented so that accurate reading is enhanced?

(2) Do visual displays have adequate means for identifying an operative condition?

(3) Have ambiguous information and complicated interpolations been eliminated from visual indicators to minimize reading errors?

(4) Do controls work according to the expectation of the operator? (Naturalness of movement direction is derived from previous experience as well as certain handedness factors.)

(5) Do functionally related controls and displays maintain functional or physical compatibility, such as direction-of-motion relationships or proximity to each other?

(6) Are controls designed so that the operator can get an adequate grip for turning, twisting or pushing?

(7) Does console design provide knee room, optimum writing surface, height, or optimum positions for controls and displays?

(8) Do equipment design and arrangement allow space for several operators to work without interfering with each other?

(9) Do arrangement and layouts stress the importance of balancing the workload, or do they force one hand to perform too many tasks while the other hand is idle?

(10) Is the illumination designed with the specific task in mind, rather than with a general situation? (Many instruments are practically useless because of lack of illumination.)

(11) Have extreme glare hazards been eliminated, such as: brightly polished bezels, glossy enamel finishes, or highly reflective instrument covers?

(12) Are assemblies and parts stacked so that some have to be removed to repair or replace others, thus complicating maintenance?

(13) Do fasteners for chassis and panels require special tools which hamper maintenance?

(14) Do chassis door slides have means for holding the unit extended for servicing? Are the slides too loose, or do they bind?

(15) Are handles provided, and are the chassis or units light enough to be moved without undue strain?

(16) Is calibration indexing provided for maintenance adjustment and calibration adjustment controls? (Screwdriver adjustments are often too sensitive.)

(17) Do the coding and symbols on equipments and in instruction manuals coincide? (Too few books tell what or how to check, what to expect, or how to correct, and when covered, the information is not organized so that it may be found quickly.)

(18) Is illumination provided for the maintenance technician?

PART IV - VALUE ENGINEERING

1. Specification Review

(1) Have the customer's specifications been critically examined to see whether they ask for more than is needed?

(2) Has the cost of any overdesign been defined for its effect on production as well as on the R&D program?

(3) Has the cost effect of contract-required overdesign been discussed with the customer?

2. General

(1) Does the design give the customer what he requires and no more?

(2) Could costs be radically reduced by a reduction of performance, reliability, and/or maintainability to the minimum specified?

(3) Could costs be radically reduced by a reduction of resistance to high temperature, shock, vibration or other environments to the minimum specified?

(4) Have circumstances changed (changes in concept or specification, progress in the art, development of new components or processes) so that the design includes unnecessary or expensive circuitry, parts or processes?

(5) Have unnecessarily high cost items been included as a result of their availability when the breadboard or model was constructed?

(6) Can any variable devices such as potentiometers included for breadboard or model operational adjustments be changed now to fixed component parts or semiadjustable designs?

3. Production Costs

(1) Are the quantities to be built on this order known? Are the estimated quantities to be built on future orders known? Have these factors been considered in the design decisions?

(2) Will tooling costs be in line with present and anticipated production?

(3) How much do you estimate the design will cost in production?

4. Electronic Design

(1) Does the design represent optimum electrical simplicity?

(2) Is circuitry overly complex or conservative?

(3) Have standard "preferred circuits" been reviewed to see how many can be used beneficially?

(4) Has the field of commercially available packaged circuits, power supplies, etc. been reviewed against your requirements?

(5) Can circuitry be eliminated by having one circuit do the job of two or more?

(6) When specifying special component parts, have potential vendors been consulted for alternatives or modifications that would hold costs down?

(7) Have all high cost components such as transistors, semiconductor diodes, magnetic and high power devices, motors, gear trains and decoders been examined to determine whether lower cost substitutions can be made?

(8) Are the components the lowest cost meeting the design requirements?

(9) Can any electrical tolerance be liberalized to allow specification of lower cost parts?

(10) Have nearly identical parts been made identical to gain the advantage of quantity buying or manufacture?

(11) Has coax cable been specified when hookup wire or shielded cable will do the job?

(12) Has silicon been specified for transistors or diodes when germanium will do the job?

(13) Can metalized Mylar be substituted for tantalum or Cerafil capacitors?

(14) Have automated techniques been used to the maximum?

(15) Is Teflon wire specified where other insulation will suffice?

5. Mechanical Design

(1) Does the design represent optimum mechanical simplicity?

(2) Is every part absolutely necessary? Can any part be eliminated or combined with another part to reduce total number of parts and cost?

(3) When specifying special parts, have potential vendors been consulted for alternatives or modifications that would hold costs down?

(4) Are mechanical tolerances within the limits of normal shop practice defined in RCA Spec. 96400? Can any tighter tolerance called out be changed to agree with RCA Spec. 96400, or be liberalized to hold costs down?

(5) Are the surface finishes the coarsest that will do the job?

(6) Are the fabrication processes the lowest cost meeting the design requirements?

(7) Have nearly identical parts been made identical to gain the advantage of quantity buying or manufacture?

(8) Are the materials the lowest cost meeting the design requirements?

(9) Does the combination of material and protective finish specified result in the lowest cost combination?

(10) Has cognizance been taken of relative workability of materials?

(11) Have standard alloys, grades and sizes of stock been specified whenever possible?

(12) Can the design be altered in any respect to avoid the use of non-standard tooling? See RCA drafting standard 8-224-200 series.

(13) Has the 1/10" grid drafting system for sheet metal parts been used wherever applicable?

(14) Can the design be modified to enable the use of the same tooling for right and left hand or similar parts?

(15) Are drawings for fabrication of parts which are similar to parts already produced cross referenced so available tooling can be used?

(16) Can the design be altered to avoid unnecessary handling and processing resulting from such things as riveting and spot welding on the same subassembly part?

(17) Have automated techniques been used to the maximum?

(18) Are casting bosses of adequate size, considering the large tolerances which apply to casting dimensions?

(19) Can cores or complex parting lines be eliminated from any casting by moderate redesign?

(20) Is impregnation of castings called out when it would aid processing? (Castings should be impregnated after machining if they are to be electroplated. This impregnation prevents absorption of plating acids or salts. Castings should also be impregnated if they are to hold liquids or gases under pressure.)

(21) Have engineering and factory specialists been consulted for castings, forgings, weldments, heat treatment and other specialties?

(22) Have standard sizes, grades and alloys of fasteners been specified whenever possible?

(23) Are all manual welding operations specified absolutely necessary? Can furnace brazing be substituted?

(24) Are the assembly processes the lowest cost meeting the design requirements?

(25) Has adequate clearance between parts been provided to allow for easy assembly? (Parts have become smaller but hands have not.)

(26) Are all parts designed for assembly at the earliest possible time? Assembly costs go up as the buildup of the system progresses.

(27) Are markings adequate to guide the assembly processes?

(28) Have the engineering and factory specialists been consulted on any unusual assembly problems?

(29) Has datum line rather than multiple surface dimensioning been used on all drawings?

(30) Can any four-place dimension be changed to a three-place dimension?

(31) Can any three-place dimension be changed to a two-place dimension?

(32) Can heat treating after forming sheet metal parts be eliminated by change of design or material to avoid straightening problems?

(33) Is all masking from finishing materials (such as plating solutions and paint) necessary?

6. Standardization

(1) Have you coordinated your design with those who may be using similar (or have used in the past) designs, circuits, parts or components to get optimum benefit from standardization and past experience?

(2) Are the standard circuits, standard components and standard hardware the lowest cost standards which will supply the minimum required characteristics?

(3) Can the use of each nonstandard part or circuit be adequately justified?

(4) Can any new nonstandard part be replaced by a nonstandard part which has already been RCA E-Form approved?

(5) Do control drawings leave no question that a vendor standard part is being specified when such is intended?

(6) Has standardization been carried too far until the cost of excess function is greater than the gains resulting from high quantity?

7. Maintainability Design

(1) Is each assembly self-supporting in the desirable position or positions for easy maintenance?

(2) Can assemblies be laid on a bench in any position without damaging components?

8. Testing

(1) Are the test processes the lowest cost meeting the design requirements?

(2) Can any test specification be eliminated or relaxed?

(3) Have interacting controls been eliminated or the adjustments specified in such a manner that the lowest cost factory test personnel can easily align the circuit?

(4) Is the system compatible with the requirements for checkout in the factory - if not as a complete system, then in large subsystem segments?

(5) Have the test process experts been consulted for alternatives that would keep their costs down?

9. Subcontract Items

(1) Has the field of commercially available packaged units, subassemblies and circuits been thoroughly reviewed to be sure there are no standard vendor items that will do the job?

(2) Is desired cost control adequately emphasized in subcontract specifications?

(3) Have our specifications for subcontract items been reviewed against the check list to be sure we are not overspecifying?

(4) Have suggestions been invited from prospective suppliers regarding possible value improvement from loosening specification limitations?

SUMMARY OF CIRCUIT TECHNIQUES FOR RELIABILITY DESIGN ANALYSIS

Just as "the kingdom was lost for want of a nail", so is it possible to render inoperable an expensive, complex command and control system for want of a reliable circuit.

It is poor design strategy to plan to apply highly reliable component parts (such as the well advertised MINUTEMAN parts) in marginally-designed circuitry and expect effective circuit performance. An important phase of an equipment subsystem design review is an examination of circuit design for reliability.

Circuit analysis techniques currently available range from a brief review of voltages, currents, and power stresses that a circuit would be subjected to, either during normal operation or at worst-case conditions, with hand computations, to computer-mechanized techniques for handling more complex circuitry and providing a more detailed analysis.

Computer orientated circuit analysis attempts to simulate a circuit mathematically on a computer and show how the performance of a circuit will behave as its basic component parts deteriorate during life. This is accomplished by programming circuit equations into a computer and methodically varying the values of the circuit's part parameters.

Very briefly, computer methods of circuit analysis entail the following steps:

a. The drawing of an equivalent circuit.

b. The writing of equivalent circuit equations and circuit requirements in terms of part parameters and reducing to matrix form.

c. Incorporating the equations, circuit requirements, and desired part parameter variation changes into a computer program.

d. Debugging and running the computer program.

e. Plotting and analyzing the computer output.

At least five well defined computer-mechanized methods are presently operational. Each method is considerably different from the other. Although it might appear that one method should be sufficient, there are two basic reasons for the multitype analyses:

a. Since there are many types of circuits in a command and control, weapon, or support system, any one method would not be the best method.

b. As detailed data on parts parameters became available, statistical methods of circuit analysis were prepared to take advantage of the new information.

Of the methods available, the Parameter Variation method requires the least amount of input data. The only necessary input data are the upper and lower limits of each input parameter. Because of their general statistical data, the Moment and Monte Carlo methods require the most extensive input data of the various methods. The Moment method requires the mean value and variance of each parameter, while the Monte Carlo method requires the entire frequency distribution of the parameter. These limitations may prevent the two methods from being widely applied.

The Mandex Worst-Case Method is based on a design philosophy which is relatively easy to comprehend; i.e., if a circuit will function properly with its parts at their worst-case condition, the circuit should operate with any combination of part characteristics as long as their worst-case condition is not exceeded.

The Mandex Worst-Case analysis has expanded this general philosophy on the assumption that there is not just one possible worst-case condition for a circuit, but one for each output variable; therefore, a complete worst-case analysis is performed on each output variable.

The name VINIL was obtained from the nature of this method of analysis where V_{IN} is swept from its minimum to maximum end of life value, and the output parameter of interest (I_L) is plotted for each sweep increment. The analysis of the results of the VINIL method is straightforward in that the graphs are simple input-parameter versus output-parameter graphs.

Returning briefly to the Moment Method, this method of circuit analysis is based on the well known theorem on the Propagation of Variance which, in part, states:

$$\sigma^2_{out} = (H_1^1)^2 \sigma_1^2 + (H_2^1)^2 \sigma_2^2 + 2H_i^1 H_j^1 \rho_{ij} \sigma_i \sigma_j + \cdots\cdots$$

where

σ^2_{out} = the output parameter variance

σ^2_n = the variance of input parameter n

H^1_n = the partial of the output parameter with respect to input parameter n

and ρ_{ij} = the correlation coefficient of parameters i and j

For normal distributions, 95 percent of the samples will fall within $\pm$ 2σ about the mean value. For abnormal distributions, according to the Tchebycheff Theorem, $\pm$ 4.5σ must be used to be 95 percent inclusive. Knowing these facts, it becomes possible to place restrictions on the mean output value by stipulating that it must be at least Aσ from some value.

SECTION IV

GENERAL REQUIREMENTS FOR A
RELIABILITY AND MAINTAINABILITY
DATA COLLECTION AND EVALUATION SYSTEM
FOR ELECTRONIC SYSTEMS

SECTION IV

GENERAL REQUIREMENTS FOR A RELIABILITY AND MAINTAINABILITY DATA COLLECTION AND EVALUATION SYSTEM FOR ELECTRONIC SYSTEMS

FOREWORD

The purpose of this section is to provide guidance to SPO Reliability and and Maintainability (R/M) Monitors in establishing requirements for a contractor's data collection and evaluation system.

Section 2 presents general requirements for an R/M Program Plan. Briefly discussed therein is the task of data collection and evaluation. This section will discuss the task in greater detail. Data collection and evaluation provides the necessary technical and management information associated with the development, checkout, and delivery of electronic systems and equipment.

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SECTION IV

CONTENTS

GENERAL REQUIREMENTS FOR A RELIABILITY
AND MAINTAINABILITY DATA COLLECTION AND EVALUATION
SYSTEM FOR ELECTRONIC SYSTEMS

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1. Introduction:

It is a well-known fact that a certain amount of foreknowledge must be possessed by a SPO of a problem before a proper decision can be made for its elimination. The same holds true within a contractor's organization. His engineering, manufacturing, and management personnel must continuously assess the equipment during all phases of design, development, production, and field use. With an accurate and complete knowledge of the problems and shortcomings concerning his equipment, it is most probable that the contractor's recommendations for changes in design and procedures will at least be of sound foundation. It is also important to know that there are no problems, if this be the case.

This pamphlet presents the basic methods and reasons for contractors to design and implement a data collection and evaluation system as part of their overall planning. It is desired that the R/M Monitor will have a basic knowledge of the salient ingredients of a data collection system for use during each phase of the overall program to the end that he can specify a system best suited for the needs of the overall SPO mission. Further, he can more properly assess the contractor's proposed plan and subsequent progress to assure that the contractor has implemented his plan to be useful and effective.

2. Time-Phased Failure and Repair Data Collections Methods and Applications:

It must be kept in mind that the task of data collection in itself is not to the end that the data terminates in a file or the wastebasket; the latter, most likely. Data collection is only one task of several in a supposedly well-conceived contractor's R/M Program Plan. Developed here are the basic requirements of a data collection system, data sources, and data uses. This pamphlet is concerned with three major phases of an overall program; namely, the design and development phase, the manufacturing or production phase, and the operational or field evaluation phase.

3. Design and Development Phase Requirements. This phase of a program is most important in that it is during this phase that system inherent availability is planned and established.

a. Data Sources. It is not unusual to expect to find various test programs being conducted at this time. Examples of these tests are those conducted at the part level, breadboard and prototype assembly and subassembly levels, and many times, at the prototype system level.

Some very meaningful R/M data result from initial teats performed in the engineering laboratory under either room ambient or controlled environmental conditions. The contractor's test engineera usually maintain notebooka which contain entries of test conditions, elapsed time indicator readings, and test results. It is expected that the contractor's collection system providas for the routine collection of these data, either by completion of failura report forma, by test personnel, or by lifting the desired data from the test logs by the contractor'a R/M personnel, or a combination of both. It is very important, during this early planning, thet due consideration be given to the total, planned test program - not only thoae teats that are to be performed during the design and development phase, but for all phasea of the overall program as aources for R/M data. It is at the beginning of a proposed program that the contractor's R/M engineers should plan and coordinate with other activities for their total data needs and the nammer in which these data will be time-phased as inputs for use during the performance of the other R/M tasks.

b. Nature of Data. When considering the kinds of data needed, thought must be given to its subsequent use.

The first and foremost reason for the contractor to collect accurate failure and repair data is to evaluate it, and detect and correct design and procedural problems as early as possible in the formulation of the design. Subsequently, the data provide necessary feedback for the determination of corrective action effectiveneas. It also provides early inputa to the verification or modification of part failure rates and feasibility of circuitry design. Some of the desired information is as follows:

(1) Equipment identifications.

(2) Test conditions and environmenta (bench test room ambient, RFI, vibration, etc.).

(3) Elepsed time indicator readings (standby end operate).

(4) Date.

(5) Test rasults.

If a malfunction occura, additional information ia needed to properly eveluate the cause; thia information includea:

(6) Failura aymptoma.

(7) Elapsed time indicator readinga at time of failure.

(8) Correctiva maintenanca action to reatora operation.

So far, reliability data haa mainly been conaidered. Of concern, also, is the kind of data in support of maintainability studies, and includaa:

(9) Time to locate trouble.

(10) Time to remove and replece faulty elements.

(11) System checkout time.

(12) Time to repair faulty element.

(13) Preventive maintenance time.

During the evaluations of the contractor's plans the R/M Monitor will be assured that the plans contain provisions for the collection of the above data.

c. Data Evaluation. Earlier in this section it was stated that the prime reason for collecting failure and repair data was to detect and correct design and procedural problems. To give an indication of the worth of these data, the typical evaluation flow will be discussed. Once the data are collected and returned to the contractor's R/M group, the following steps should then take place on each completed data form:

(1) R/M engineers screen data entriea for completeneas and technical validity, utilizing drawings, part purchase specifications, and test procedures. Any imcomplete or wrong entries are rectified as aoon as poasible.

(2) If a contractor's plan calls for coding of raw data, the engineer indicatea proper code for technical data. This includes the coding for failure effect on system operation (inoperative, intermittent, etc.), cause of failure (part failure, test error, incorrect fabrication, etc.), and responsibility (Quality Control, Design Engineering, User, etc.).

(3) Data reports are put in final code form for keypunching by data processing personnel. Resulta of failed parts analysis are integrated with failure data.

(4) Tabulations of reduced data are evaluated by statisticians for MTBF, MTTR, and failure trends, and by R/M engineers for weak linka and design deficiencies. The data may also be retrieved in requaated aequence in support of special atudies; i.e., failure histories of given equipments, part applications, and/or other trouble areas.

(5) Results of studies and evaluations by the R/M engineers are fed back to the appropriate activity in the corrective action feedback loop - design problems to the design engineering, manufacturing problems to the Quality Control activity, vendor problems to the procurement activity.

(6) Results of corrective actions effectuated are fed back to the R/M activity and are used to up-date mathematical models and predictions of MTBF and MTTR.

4. Manufacturing or Production Phase Requirements:

a. Data Sources. To fully understand the worth of production R/M data, it is necessary to first consider the basic concepts of inherent R/M and operational R/M. Inherent R/M may be defined as the reliability and maintainability potential present in the design; i.e., that which is designed in. This R/M potential may be achieved at the site - operationally - if there is no degradation due to fabrication and assembly. Operational R/M is the R/M demonstrated in a service application. In the case of reliability, it consists of inherent reliability degraded by manufacture, test, shipping, handling, storage, maintenance, and use. Practically the same may be said about the degradation of inherent maintainability.

As sources of data, then, the SPO R/M Monitor will look to the areas and agencies responsible for the degradation of inherent R/M; namely, manufacturing (production), handling, storage, maintenance, and test.

b. Nature of Data. Data can be separated into broad categories as quality data and R/M data. Quality data includes records of inspection and testing; e.g., go-no-go tests, measurements of variables such as resistance and capacitance to determine conformance to established technical requirements contained in specifications, drawings, and purchase orders. R/M data on equipments are developed during preproduction stages in order to detect equipment weaknesses before release to production and to obtain a quantitative estimate of equipment R/M. R/M data on parts and/or components are developed during the production stages to assure that the equipment inherent R/M is not unduly degraded by manufacturing processes. When the data indicates excessive failure rates or excessive times to repair, this information must lead to corrective actions.

In designing a failure and repair form, the following minimum items will be considered for inclusion:

(1) Report serial number.

(2) Report activity.

(3) Reported by (name or individual).

(4) Date of report.

(5) Date of malfunction.

(6) Geographical place of malfunction.

(7) Reference or circuit designations.

(8) Name of item that malfunctioned.

(9) Name of manufacturer of the item.

(10) Manufacturer's part number.

(11) The item's serial number.

(12) Symptom of malfunction.

(13) Type of malfunction.

(14) Environment at the time of malfunction.

(15) Elapsed time to failure or malfunction.

(16) Clock time to isolate failure cause.

(17) Clock time to actually repair.

(18) Clock time equipment was down for repair.

(19) Action taken to clear malfunction.

(20) Requirement that part be forwarded to reliability organization for analysis.

(21) Recommendations and/or comments.

Paragraph 3.5.12 of MIL-R-27542A should be referred to for a more complete listing.

c. Data Evaluation. A prime reason for accumulating and analyzing failure and repair data during the production phase is to evaluate the R/M being achieved during the fabrication stages. Data relating to failure and repair should be forwarded to the contractor's R/M groups. It should be the responsibility of this group to evaluate the need for further analysis to determine the cause of failure or to make this determination by utilizing existing data. Figure 1 is a typical, basic R/M information flow between a

contractor's activities. It also indicates inputs from the field, and feedback to the SPO. Referring to this figure, it is obvious that data are not collected for the sake of collecting data. It should be noted that it is the responsibility of the R/M group to disseminate to the various interested groups information which clearly indicates the need for improvement in their respective areas of responsibility and to provide follow-up to assure that adequate corrective action is undertaken. Figure 2 presents a typical data flow within the contractor's R/M activity. Outputs from such an activity include tabulated and analyzed failure and repair information, and most important, recommendations for corrective actions. The following steps should be taken by the contractor on all data:

(1) The R/M engineers screen all failure and repair reports to determine their technical validity, and then classify failure information as to:

(a) Effect of the failure on system performance.

(b) Cause of failure.

(c) Responsibility for corrective action.

(2) The classification activity is supported by the results of analyzing failed parts and assemblies.

(3) Weak links are identified, and MTBFs and MTTRs are calculated.

(4) Recommendations for corrective actions to eliminate weak links are generated and disseminated with substantiating information; mathematical models are updated.

(5) Most important, recommendations are followed-up to determine that suitable corrective action has been taken.

Figure 3 presents a typical corrective action flow process that a contractor should undertake to effectuate recommendations for corrective actions submitted by his R/M activity. A plan similar to this should be company policy and is something the SPO R/M Monitor will look for in appraisal of the contractor's policies, procedures, and plans for implementing an effective R/M activity. This process is satisfactory for use during all phases of the contract, and is presented at this time, within the comments pertaining to the manufacturing or production phase, as a matter of convenience.

5. Operational or Field Evaluation Phase Requirements:

a. Data Sources. Obtaining timely, accurate, and complete R/M data from the field is probably the most difficult to achieve. This is often true due to incomplete, or lack of, early planning or people are too busy attempting to get the equipment to function, which is their prime mission. Nevertheless, an initial, well-conceived data collection plan which is properly coordinated with all concerned should reduce data collection to a routine activity.

Data sources include operational logs, contractor's report forms, and report forms associated with AFM 66-1; namely, AFTO Forms 210 and 211, Maintenance Discrepancy/Production Credit Records; and 212, Time Compliance Technical Order Work Record. These latter forms were designed primarily to serve as source documents for the maintenance data collection system for aircraft. However, the system is currently being modified to be more appropriate for use by all Commands.

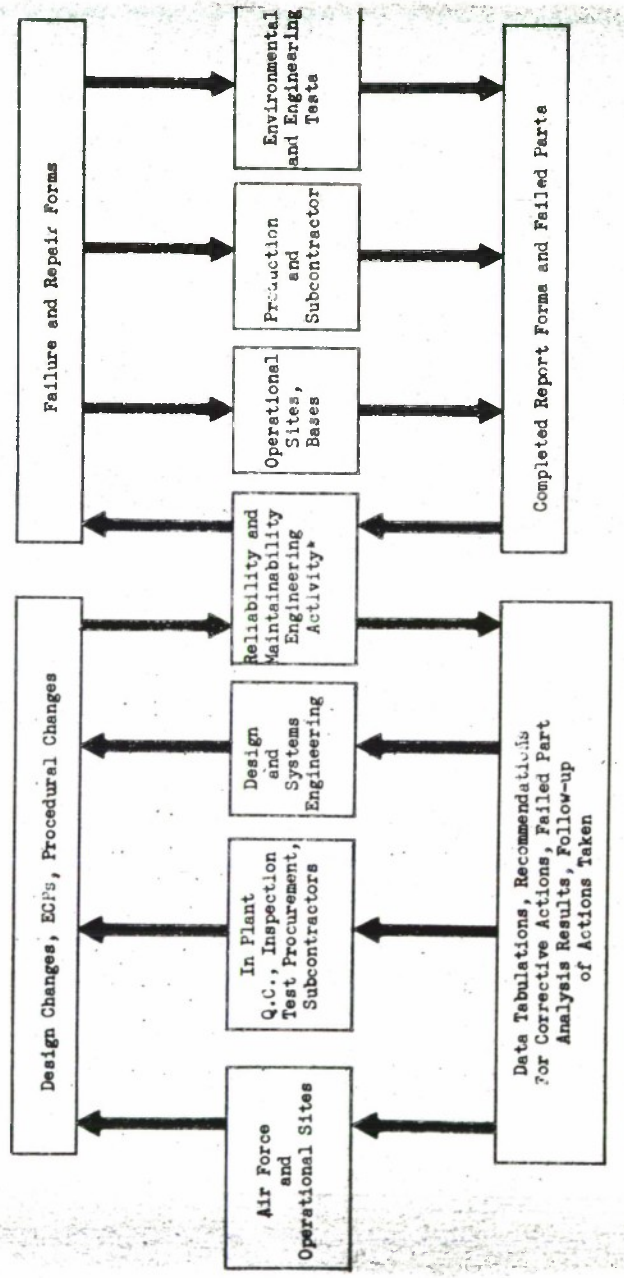
b. Nature of Data and Evaluation. The types and evaluation of field failure and repair data are much the same as described in earlier paragraphs. However, greater emphasis is given to operational malpractices and incompatibility between inplant performance specifications and operational specifications. During the operational phase of a given program, the contractor's R/M engineers should be exerting a great deal of effort to uncover these causes for equipment and system unavailability. To achieve this end, the R/M engineer must be provided with both quantitative and qualitative information pertaining to a failure. As an example of this, if a magnetron is reported as having failed, the data collected should answer the following questions: What parameter was out of specification? What was the actual reading? What should it be? According to what document? Provided with answers to these questions the R/M engineer should be able to methodically evaluate the event by checking documents such as drawings, performance specifications, purchase specifications, procedures, operating manuals, etc., and comparing this information with that reported. Given adequate information, the R/M engineer can then recommend, if necessary, a corrective action to the appropriate activity along with definitized statements about any existing discrepancies.

Field failure and repair reports also provide inputs for the determination of achieved quantitative reliability and maintainability. From these documents is lifted the time information associated with times-to-failure and times-to-repair which are used in subsequent calculations of MTBF, MTTR, and MDT. Together with the AFTO Forms, these data provide inputs to the SPO, Using Commands, and AFLC for the determination of logistics support, types and quantities of spares, number and grades of maintenance personnel. To give a measure of the worth of field failure and repair data to USAF, the following is quoted from page 1-3 of AFM 66-1:

"1-14 Data Collection - The manhour accounts and maintenance data collection procedures outlined in this manual are continuously assuming greater importance in the Air Force. (Note: The maintenance data collected can be adequately processed by PCAM methods. This method affords the flexibility necessary to readily compile data essential to maintenance management.) Manpower criteria is to be based upon this data. Besides the use of the recorded elements of data by base level management, the same data is used extensively throughout AFLC management levels, for many purposes. Some specific AFLC uses are: analysis of the high system failures and the high system consumer of manhours by weapon system; identification of items and substantiation for product improvement action; analysis of established inspection requirements and a basis to adjust inspection criteria; analysis and adjustment of the component time change cycles; analysis of the not repairable this station (NRTS) listing; computation of spares requirements based on usage in lieu of the SB and CR; and aerospace vehicle selected equipment configuration status recording. The significance of these and other uses of the data for management throughout the entire materiel function makes it imperative that elements recorded be accurate, that quality data is accumulated. In view of this large-scale AFLC-wide usage of the data, in addition to base-level management usage, it is obvious that data accuracy and coverage is of extreme importance. The Chief of Maintenance must continuously act to insure that all assigned personnel are providing 100% coverage and accuracy in these data recordings. He must also insure that work center supervisors are checking input data on the original documents, each data, for accuracy and completeness. In addition, commodity information will be used for supply consumption reporting, by programs and master repair schedule. Accounting and budget data is also being obtained from this data."

It is extremely important that the contractor's reporting system is compatible with the requirements of AFM 66-1. This will afford ease in the transition from a contractor-maintained site to USAF (blue-suit) operation (usually prior to Cat II tests). Since AFM 66-1 is in great detail, it will be well for each SPO R/M Monitor to review it to become familiar with its general content and requirements.

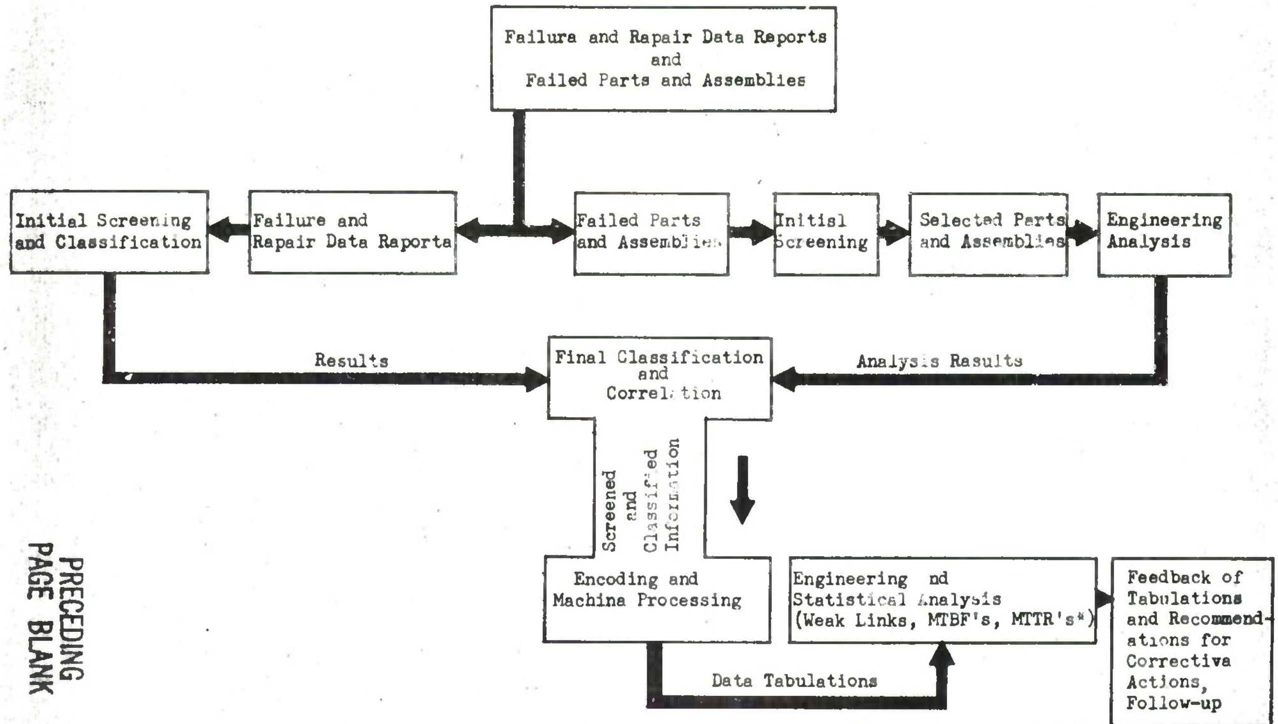
Typical, Basic R/M Information Flow



*See Figure 2 for processes internal to contractor's R/M activity.

Figure 1

Typical Data Flow Within Contractor's R/M Activity



*See Figure 3 for details.

Figure 2

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Contractor's Typical Corrective Action Flow Process

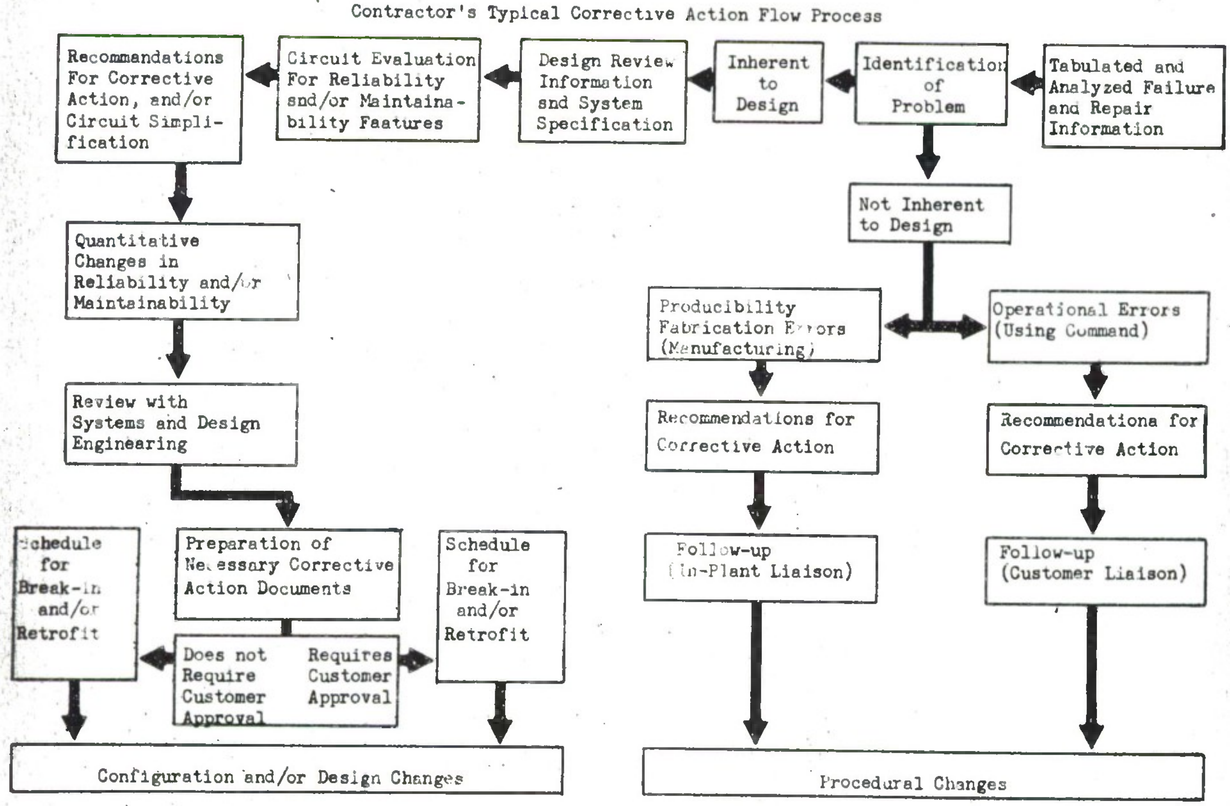

Figure 3

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SECTION V

RELIABILITY DECISION MAKING - CONSTRUCTION AND APPLICATION OF PROBABILITY OF ACCEPTANCE CURVES

SECTION V

RELIABILITY DECISION MAKING - CONSTRUCTION AND APPLICATION OF PROBABILITY OF ACCEPTANCE CURVES

FOREWORD

Current statistical literature gives little guidance in choosing between various statistical methods and choosing "proper" levels of risk. These considerations are mostly left to the unaided judgement of the decision maker.

This section takes several statistical procedures and places them within the same overall framework, in order to provide a base for objectively choosing between them. The reader is also directed to Probability of Acceptance curves as an aid to selecting producer and consumer risk levels. Finally, a tabulation of the advantages and disadvantages of each of the various methods is presented.

CONTENTS

ILLUSTRATIONS

ATTACHMENTS

Chapter 1

INTRODUCTION

This section has a three-fold objective: (1) to give ESD's position on current methods for selecting statistical accept/reject criteria in order to reach decisions on equipment reliability; (2) to discuss recurring demonstration problems (unique to ESD procurements) and certain statistical methods, not available in current statistical literature, for dealing with these problems; and (3) to present those mathematical concepts and methods that must be understood by those responsible for the successful management and implementation of reliability programs.

The need for this section arises from the fact that "statistical decision theory" is a comparatively new and rapidly changing field. Thus, there is no single document that one can select to extract the same information given here. Rather, a laborious and time consuming study of many forbidding treatises is required and, even then, one is likely to encounter difficulty in piecing together isolated results which might apply to a given situation.

Furthermore, several reliability demonstration specifications are in the the process of being revoked and replaced by a single military standard (which, at this writing, has not as yet received a numerical designation). The new Standard is based upon ideas explained in this section and contains numerous test plans (decision rules) for demonstrating equipment reliability. In order to use the Standard, one must consider several things, such as: Mean-Time-Between-Failure (MTBF) requirements and associated failure definitions; the intended operational environment and associated stress testing that is warranted; the amount of test time that may be allotted and associated risks that may be tolerated in making accept/reject decisions.

Since our subject is technical, one must become familiar with certain concepts upon which the entire subject is based. If the reader has difficulty absorbing these concepts, he should keep in mind that most often the trouble is caused by the language that is used. Habitually, ordinary words are used in special senses; a practice that is convenient if one has mastered their use, but disconcerting if one has not. In any case, the language must be endured, since once it has developed only minor changes are feasible.

This section is written with these thoughts in mind. With the exception of Chapter 3, "Technical Considerations", great pains are taken to present concepts and methods with a minimum of technical jargon and notation. In Chapter 2, particularly, the style is deliberately wordy; and although a certain amount of special vocabulary and symbolism is required for efficiency of thought, only those which are considered essential to explain key results are used, however convenient it might be to do otherwise.

Similarly, certain significant topics are deliberately excluded (such as "methods for confidence interval estimation") because of the many technical details required to give them adequate explanation, and because knowledge of these topics is not considered essential for the results obtained herein. While the discussion of related topics may have broadened the scope of this section the risk of creating confusion on the part of the uniniated reader demanded that such topics be omitted.

Chapter 2

MANAGEMENT CONSIDERATIONS

1. Background - Measuring Reliability. In studying the behavior of a physical process, a conceptual (mathematical) model is sought which will bring together certain observed variables in order to derive meaningful and unambiguous statements which gain universal acceptance. Hopefully, the establishment of an idealized mathematical structure permits a quantitative characterization of the process that enables us to predict its future behavior as a result of analyzing data.

The discipline of Reliability Engineering has established such a structure, that is, a quantitative basis for measurement, and is continuing to build upon it. Indeed, some define Reliability as the science that predicts mathematically the failure behavior of a particular device. Quite commonly, one finds Reliability Engineers involved in "distribution theory" or the application of probabilistic laws, in order that they may describe the interactions of parts, equipments, and systems.

It didn't start out this way. In the beginning, Reliability was treated more qualitatively. As recently as the early 1950's, there were severe arguments over the definition of Reliability - some held that it was a "feeling" that a collection of equipments, people, etc., would yield desired results. At this time there was concentration on data collection, classification, and engineering analysis of data to lessen the frequency of failures. One may tersely describe the underlying attitude that prevailed in this period as a "build-fly-fix" philosophy.

Reliability entered a "management era" in the mid-1950's, during which time there was a struggle to develop standard terminology, and techniques for organizing a reliability program. Major accomplishments during this period were studies performed by Aeronautical Radio, Incorporated (ARINC), which eventually led to the development of the first Reliability prediction technique for airborne bombing navigation equipment, and Radio Corporation of America (RCA), which presented the interaction between operating stress levels and part failure rates. These efforts provided a basis for designing Reliability into electronic equipments and, when coupled with the fact that exotic demands on the performance of electronic equipments were having such disastrous effects on their reliability, made it imperative that acquisition philosophy change to: "build-it-right-the-first-time."

Moreover, complexity of electronic equipment was continually increasing, making it mandatory that methods for quantitative analysis be developed. Efforts toward this end culminated in the AGREE* Report, 1957, issued by the Assistant Secretary of Defense, a milestone in Reliability documentation. Several military specifications arose at this time requiring that quantitative Reliability indices be established and

* Advisory Group on Reliability of Electronic Equipment

demonstrated before committment to operational usage.

Thus, by 1960, Reliability emerged as a new discipline. Separate military staffs and industrial departments appeared on the scene, as well as text books and research reports all apparently aimed at refining the mathematical aspects of the theory of Reliability. Emphasis was placed upon statistical methods for estimating the degree of reliability that was being achieved.

Yet, as the use of mathematical concepts increased, the amount of special terminology and notational devices needed to intelligently discuss the subject also increased, and those not fully engrossed in the field became less familiar with its progress. It became apparent that Reliability was being measured without regard to several important factors, such as the intended use of the equipment, cost of testing, schedules, and equipment characteristics. In many cases, the statistical refinements were excessive causing unnecessary delays in decision-making or, what is worse, waiving of all demonstration requirements. On the one hand, lengthy tests had been specified, by <u>other</u> than program managers, in order to "prove" reliability, and on the other hand, management had created schedules which were incompatible with such testing.

There is perhaps only one way to avoid this situation, that is, if program managers ask themselves one important question: "Why are we measuring Reliability?" Related questions are "Do we need close estimates of actual numerical values, or is it sufficient to simply give reasonable assurance that these values are above minimum levels? What are these minimum levels and how much test time may reasonably be devoted to this effort? How does adding or subtracting test time affect our assurance that such requirements have been met?"

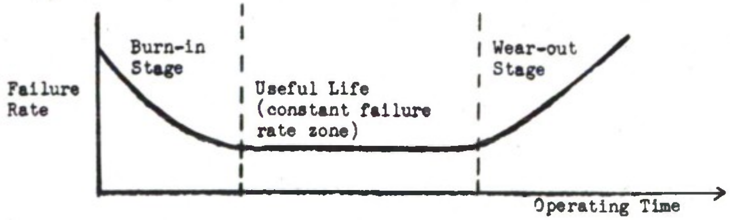
2. <u>Measures of Reliability</u>. Usually, the above questions are not difficult to answer if quantitative measures for the reliability of the equipment or system under consideration have been established. Thus, before explaining methodology for making this analysis, it is necessary to explain certain measures which have been found to apply to large classes of electronic equipment.*

* Readers with previous experience in this subject may, of course, skip paragraph 2. Since this statement may arouse their curiosity, it may be appropriate to set forth what we have tried (and not tried) to accomplish. We have attempted to give those with <u>no</u> previous experience, an intuitive grasp of <u>one</u> method for establishing quantitative reliability measures in order to explain certain problems that arise in designing demonstration tests. Hence, this is not a precise, systematic, or all-ioclusive development - experts may detect areas of over-simplication, or even errors; although, of the latter, none were intentionally included.

In what follows, it is helpful to distinguish between two types of electronic devices. One would be a device that is designed for continuous operation and comprised of two or more replaceable sub-units (or parts). It is also designed so that a failure of any of these sub-units (parts) causes the device to be inoperable, and restoration is made simply by replacing the malfunctioning sub-unit. For this type of device, it is not surprising that most people are concerned about the question "how long, on the average, does it operate between consecutive failures?" This question is usually answered by giving its "mean-time-between-failure (MTBF"). On the other hand, some people, not quite so far-sighted, may be apprehensive about the very next failure and may phrase their question "how long, on the average, before the first failure?" This is really the same question as before (but with a different orientation) and receives the same answer except that it is verbalized as "mean-time-to-failure (MTTF)". This response is a commonplace when dealing with a second type of device, namely, one with no replaceable sub-units besides itself. Thus, failure of the device means its "death", and it is for this reason that MTTF is sometimes referred to as "Mean Life".

It is only natural to speak in terms of devices of the first kind since they occur most frequently in ESD procurements. Two important advantages accrue from this choice. One is that the single word "equipment" may be employed throughout, when referring to these devices. The other, perhaps more important, is that the reader is never thinking of the wrong example. Thus, the expressions MTTF and Mean Life will not be encountered again.

That MTBF is measurable is the theme of ensuing paragraphs. Its development, however, depends on a number of assumptions. The first and most far-reaching assumption that shall be made is that MTBF is a fixed quantity, say 5, 200, or 10,000 hours, depending on the design of the equipment (and, possibly, its environment). Naturally, one could not expect MTBF to be a fixed quantity for the entire life of the equipment. The following curve:



known as the bath-tub curve, illustrates that equipments exhibit their best "failure behavior" after certain manufacturing and design errors are removed (during what is commonly called the "burn-in stage") and before rather extensive replacements become required as a result of age (or wear

out). The period between the burn-in stage and the wear-out stage is called the "useful life", and it is here that MTBF, as a fixed value, takes on its true meaning. The expression "failure rate" is defined as the reciprocal of MTBF (i.e., if the MTBF is 200 hours, we expect failures to occur, on the average, once each 200 hours so that 1/200 is termed the failure rate).

Another important assumption is that failures occur at random. For those not familiar with probability theory, this may seem to contradict the assumption that MTBF is a fixed value (during the useful life of the equipment) but there is no contradiction. Consider, for example, the occurrence of a "seven" upon the tossing of dice. Although this occurrence is quite unpredictable on a single toss (therefore random), most would agree that for the case of unloaded dice betting against such an occurrence on repeated tosses would cause us to win, on the average, 5 out of 6 times. Thus the "mean-tosses-between-sevens" may be considered a constant, in spite of the fact that, occasionally, we experience 3 or 4 "sevens" consecutively and the absence of a "seven" on 10 or 11 repeated tosses is not uncommon.

Hence, long runs of failure-free operation average with short runs of repeated failures to give an overall value that is considered the equipment failure rate. One may be tempted to take the number of failures that occur and divide it by the total operating time to obtain an estimate of the failure rate just as one usually divides the number of tosses which yield a "seven" by the total number of tosses to help decide whether dice are biased with respect to the attribute "seven". But one does not have to be an expert in statistics to realize that this procedure gives erroneous results quite often due to "chance fluctuations", particularly if small amounts of data are collected. In fact, one can say that the main role of statistics is to develop procedures for coping with this problem. Most likely, it has already occurred to the reader that the procedure just explained works quite well if "enough" data is collected, that is, the well known "law of averages" begins to operate after a while leaving little doubt in the minds of reasonable people. Thus, if 5,000 "sevens" occur in 10,000 tosses, one does not need advice from experts to decide that the dice are biased.

So far, the implication has been made that MTBF is a measure of reliability, but the relation between the two or, more precisely, the effect that MTBF has on reliability has not been stated. To do this requires a definition of the word, a matter that has been neglected until now. Therefore, without further ado, reliability is defined as "the probability of failure-free operation for a given amount of operating time". This is a good working definition which gets the point across that reliability is a probabilistic notion as well as a function of time, and it should not shock anyone that the resulting probability is quite dependent upon the MTBF of the equipment under consideration.

This is all that shall be said about "measures of reliability" since Section VI,   "Verification of Quantitative Reliability Requirements", give a more detailed discussion of this matter. In that document, the problem of measuring reliability using specific methods is discussed; here, the problem is to develop methodology for choosing between various methods.

3. <u>The Demonstration Problem</u>. The preceding discussion already gave hints as to the difficulties associated with drawing inferences about reliability as a result of a demonstration, namely, that almost any failure behavior could be consistent with any value of MTBF. This problem becomes acute when short periods of testing are involved, but is chronically present even when long periods of testing are permitted.

"Long" and "short" are, of course, relative terms, which mostly depend upon MTBF requirements for their meaning. For example, 500 hours is considered a lengthy test for a 10 hour system, and quite brief for testing equipments with MTBF's of 1,000 hours or more. For production procurements 5,000 hours may not be considered a long demonstration if enough models can be tested simultaneously and their operating times and quantities of failures are combined. (This is permitted, statistically speaking, as long as enough time is accumulated on each equipment to insure that they have progressed beyond the burn-in stage.)

Unfortunately, ESD is mostly confronted with non-production procurements and high-order MTBF requirements (say 500 hours or more). In fact, one must usually keep in mind that only about 720 calendar hours are available each month. It becomes extremely difficult to design a test that is long enough so that some failures can be expected to occur. Clearly, little is gained by observing failure-free operation in a given operating time if one would not even expect unsatisfactory equipment to have any failures in that time.

Still it appears that one is forced to make decisions about MTBF based upon the number of failures that occur (if any) in a given amount of operating time. It is easy to see that the Air Force cannot establish a decision criteria that <u>always</u> rejects equipment with MTBF's that are inconsistent with specified requirements, since such a criteria would also reject <u>satisfactory</u> equipments too often. More specifically, there are two types of risks present. They warrant special names because they must be carefully scrutinized in any statistical decision rule of this kind. These are:

Air Force Risk: The probability that unsatisfactory equipment will be accepted.

Producer Risk: The probability that satisfactory equipment will be rejected.

Chapter 3 of this pamphlet gives detailed methods for quantifying these risks and keeping them below prescribed levels when making accept/reject decisions, and Chapter 4 gives an analytic discussion of how low risks affect the required test time. It becomes apparent there that risks cannot be established without considering the amount of test time that is available. Hence there cannot be a single decision rule that applies to all procurements.

Another closely related problem, but one which has little to do with probabilistic concepts, concerns the MTBF requirement. It has become customary to cite a single figure, say 500 hours, as the minimum acceptable value, and then require that this value be demonstrated. Such a requirement may be unreasonable from two distinct viewpoints. From a practical view, it does not seem plausible that 500 hours is acceptable but 499 is not. Moreover, those who are statistically oriented shudder at the thought of satisfactory and unsatisfactory values being separated by a hair-line, a situation that is certain to play havoc with the "risks". It turns out (as pointed out in Chapter 3) that under these conditions, if the Air Force maintains its risk at 10%, the producer's risk must be 90%, that is, both risks must add to 100%. There is perhaps only one way to avoid these high risks. If operational requirements call for a 500 hour MTBF, then this <u>must</u> be the value that is labeled "satisfactory", and should be used for determining the producer's risk (how this determination is made shall be covered in Chapter 3.) However, those values just below 500 hours cannot be termed unsatisfactory, since it appears more reasonable to specify an "MTBF lower bound", say 450 hours, such that it becomes a matter of concern if the MTBF should be this low (due to the deteriorating effect on operational effectiveness). Thus, MTBF's less than or equal to 450 hours are termed "unsatisfactory" and the Air Force risk may be computed based on this number rather than 500. This number (500) could be called the "MTBF upper bound" or "MTBF objective". Here too, it is ludicrous to say that 451 hours is satisfactory, that is, all that can be said about values <u>greater than 450 but less than 500</u> is that they are neither satisfactory nor unsatisfactory. Under a stipulation of this kind it is possible to hold both risks at relatively low levels. The details of doing so shall be explained in Chapter 3.

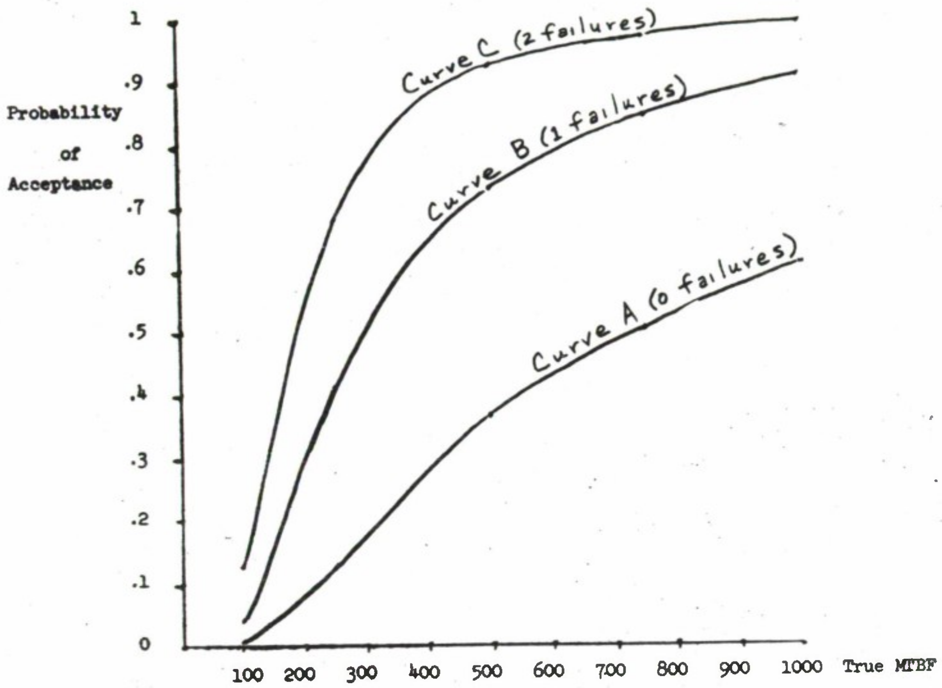
One last problem worth mentioning because it is frequently not adequately considered, involves the definition of "failure". This problem is not solved by reliability specialists alone--there are both engineering and operational requirements to be considered. Similarly, how the equipment is to be exercised during the demonstration is a factor that requires some thought if the demonstration is to have any relation to the intended use of the equipment. At this point, it should be noted that the "intended environment" was left out of our definition of Reliability, in order not to clutter up our math model. This, of course, must be compensated for by those designing or specifying the conditions of test.

4. <u>Choosing Accept/Reject Criteria - Use of Probability of Acceptance Curves</u>. Once meaningful requirements have been stipulated, it remains to establish an accept/reject criterion for the demonstration. There exist military standards and specifications which give specific accept/reject criteria to be used for demonstrating reliability of electronic equipment. These may be helpful in some cases, but cannot be used indiscriminately. They are based upon procedures which attempt to hold both Air Force and producer risks below certain levels, but all involve a certain amount of operating time before decisions may be made. Naturally, one should choose the one that gives the least risk consistent with the amount of time that may be expended for demonstration purposes.

Another method exists for choosing between available accept/reject criteria. In Chapter 4 the construction and application of "probability of acceptance curves" (PA curves) is described. For any particular criteria that we select, these curves will give, at a glance, the probability that equipment with various levels of true MTBF will be accepted--that is, pass the test. Hence, the producer can derive design goals which give near-certainty of being accepted or, at least, very low risks. On the other hand, the probability of accepting low quality equipment is also made apparent, thereby causing responsible Air Force officials to take an active interest also.

For example, suppose that the MTBF lower bound is 400 hours and the MTBF upper bound is 500 hours. Then, as previously noted, values of true MTBF less than or equal to 400 hours are considered unsatisfactory and values of true MTBF greater than or equal to 500 hours are considered satisfactory. Now, let us suppose that two models may be placed simultaneously on test, (with the agreement that their operating times and numbers of failures shall be combined) but, either the cost of testing or "tight" schedules prohibits more than 500 hours of reliability testing. Hence, the number of failures permitted for acceptance purposes must be decided upon. For simplicity, let us try to decide between 0, 1, or 2, by using PA curves.

Figure 1 (see next page) shows the PA curves for 0, 1, 2 failures allowed, respectively, in 500 hours of test. Looking at Curve A we see that even if the producer has designed equipment with true MTBF equal to 1,000 hours (400 hours above the requirement), the probability of acceptance is only about 60%; hence, this test (0 failures allowed) may be considered too severe. On the other hand, Curve B shows that equipments with true MTBF equal to 250 (250 hours less than required) have a 40% chance of being accepted; hence, this test (1 failure allowed) may be considered too lenient. Clearly, the producer would be satisfied with 2 failures allowed (Curve C) since this rule would give better than 90% probability of acceptance for any value equal to or better than the 500 hour requirement. But such a rule allows 400 hour equipments (which are considered unsatisfactory) better than 80% chance of being accepted.



Curve A: 500 test hours, 0 failures allowed

Curve B: " " " , 1 failure "

Curve C: " " " , 2 failures "

FIGURE 1: PA CURVES FOR 500 HOURS

Obviously, none of these decision rules will satisfy both parties. Either, more test time must be obtained, or upper and lower bound values must be re-examined. For example, the decision rule depicted in Curve B might be reasonable if the lower bound value were 200 rather than 400 hours. In other words, if the procuring agency determined that values of MTBF between 200 and 500 hours would not drastically affect operational effectiveness, the allowance of 1 failure in 500 hours of test gives reasonable assurance to both parties.

However, suppose test time could be increased to 1,000 hours (possibly by doubling the number of models simultaneously tested, or as a result of rescheduling). Let's now look at PA curves for 0, 1, 2, and 3 failures allowed (see Figure 2, next page) in 1,000 hours of test.

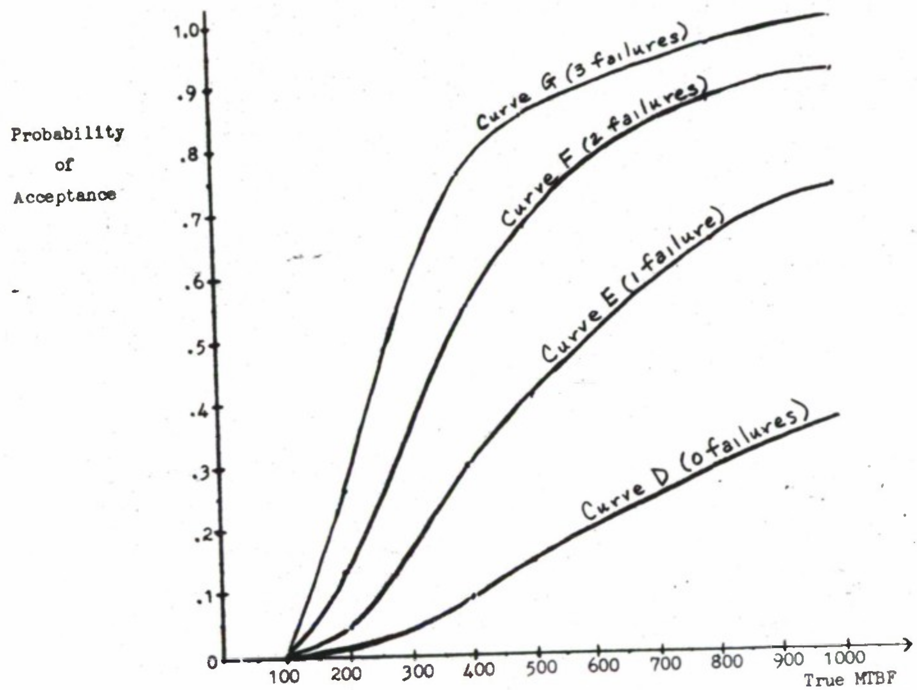
Using the same reasoning as before, it appears that Curve F (2 failures in 1,000 hours) comes closest to satisfying both parties, although both would have some reservations about such a decision rule.

All examples used thus far have assumed that a fixed amount of testing would be conducted and a certain amount of failures allowed for acceptance, say x, with the implication being that if x + 1 or more failures occur in that time then a reject decision would be made. It was also assumed that test time was extremely limited, relative to the MTBF requirement; that is, in the first case (500 hours) we could only test one multiple of the MTBF requirement (also called "MTBF upper bound" or MTBF objective,") and in the second case (1,000 hours) only 2 multiples of MTBF testing was permitted.

When 3 or more multiples of MTBF testing are permitted, risks may be held much lower and, in fact, earlier decision points may be stipulated. To see this more clearly, observe that Curve A of Figure 1 shows that after 500 hours of testing, if no failures occurred, the probability of acceptance for equipments with MTBF less than or equal to 400 hours is at most 28%. This "worst case" probability may be called the Air Force risk, representing the "probability that unsatisfactory equipment will be accepted." What we are saying, then, is that if the Air Force accepts on the basis of 0 failures in 500 hours, there is a 28% risk.

Now, if risks below (say) 30% can be tolerated, the Air Force could accept at this point. But what about rejection? Another glance at Figure 1 (Curve B, this time) shows that equipments with MTBF's of 500 hours or more have at least 72% chance of passing, if 1 failure were allowed. This may be reinterpreted as follows: Such equipments have only 100% - 72% = 28% chance of having 2 or more failures in 500 hours. This again is a "worst case" probability, and may be called the producer's risk.

Hence, after 500 hours of test, the Air Force could accept if 0 failures occurred and reject if 2 failures occurred, with (at most) 28% risk to both parties. Of course, if exactly 1 failure occurred in that



Curve D: 1000 test hours, 0 failures allowed.
Curve E: " " " , 1 failure " .
Curve F: " " " , 2 failures " .
Curve G: " " " , 3 " " .

Figure 2. PA Curves for 1,000 Hours.

time, no decision could be made, but the test could be continued and at various points during the test (say, at each multiple of MTBF) the same kind of determination made. Eventually, a point would be reached where the number of failurss specified for acceptance is one less than the number of failures specifisd for rejection, with both risks bsing the same.

The ideas explained in the preceding paragraphs come under the name "sequential testing", and specific procedures for devising such tests are detailed in ESDP 80-5. We may conclude our comments here by saying that sequential tests should be used whenever the amount of test hours permitted is sufficient since prescribed levels of risk ars never violated and yet, more often than not, early decisions are reached. Psrhaps this is caussd by a tendency for equipments to be "extremely good" when they meet requirements and "extremely bad" when they don't. Of course, if sufficient test time is <u>not</u> available, one must resort to the fixed-time approach.

The chapters that follow shall first cover the basis for various decision rules, some of which have been briefly explained in this chapter, and then give a comparative analysis of these rules, citing advantages and disadvantages of each for different applications.

Chapter 3

TECHNICAL CONSIDERATIONS

1. Designing Test Criteria:

a. Introduction. In any scientific endeavor gathering of data is usually a meaningless exercise unless one first establishes pertinent hypotheses and then focuses on the question "how well do these facts fit the given hypotheses?" In other words "the facts usually don't speak for themselves." If, in turn, the data is quantifiable and the hypotheses take mathematical form, it is usually a simple matter to state an unambiguous criterion for accepting or rejecting the given hypotheses. However, there are two major problems associated with the establishment of an accept/reject criterion. One is that, having quantified the data, such quantities as are derived from tests or experiments appear random in nature (sometimes called "chance fluctuations"), that is, having knowledge of previous results does not enable one to make precise and meaningful predictions about the very next result. The other is that additional methods are required to determine how good or how bad the accept/reject criterion is. Does it, for example, consistently make correct decisions? How do we define "correct", and how do we compare differing criteria that may be contemplated? It would be nice if we could order them in such a way that the one at the top of the list would be best to use, but unfortunately this is not always possible. Still, it is possible to cite advantages and disadvantages of each for a particular application, and then give the rationale for the choice one makes. Here, several choices shall be presented and compared in this manner. Before doing so, it is necessary to give a general discussion of the process which quantifies data and makes decisions on the basis of the collected data. In what follows this process is called a "decision-rule". No attempt shall be made to give a systematic theory of decision rules, since this requires more time and space than is at our disposal. Rather, it is intended to reflect the "modus operandi" of decision making.

b. Elements of Decision Rules. Most decision rules begin by making certain assertions (not to be confused with hypotheses) concerning the nature of the situation that is involved. These assertions (called axioms) are the result of observation (experience) and usually are so basic that attempts to justify them meet with frustration and ultimately with despair. (For example, the basic laws contained in Attachment 1.) Happily, few ask to have them justified, that is, they are accepted by most people as being self-evident. These axioms always contain undefined concepts which take on meaning when a particular application is called for. The next step is to derive certain theorems from these axioms by means of logical argument. Finally, these theorems are compared with observed data and reinterpreted in order to establish a rule of procedure which tells us whether to accept or reject certain hypotheses or to continue the experiment until sufficient data is collected.

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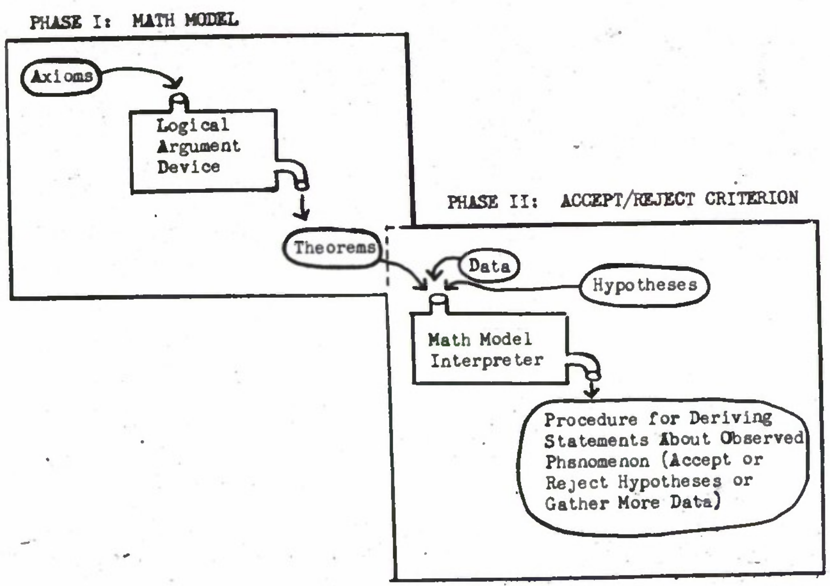
More briefly, a decision rule contains two major ingredients: (1) a mathematical model of the observed phenomenon; and (2) an accept - reject criterion which takes collected data and reinterprets statements concerning the model into statements about the observed phenomenon[1]. These ideas may be summarized pictorially as follows:

DECISION RULE MACHINE



1. The following remark is for the benefit of those who may recognize a similarity between the following discussion and "Tests of Hypotheses", as covered in statistical texts. There, (2) is thought of as the decision rule itself, and (1) remains hidden. One reason for this is that a certain type of mathematical model exists (called a probabilistic model) which is "a model of a mathematical model." This permits the development of a specific mathematical model simply by making inputs to the more general model. These inputs may be stated generally (e.g., a density function) and the rule of procedure can simply call these out so that the mathematical model is created as the rule of procedure is applied. Whether or not it is reasonable to use the same rule of procedure for differing mathematical models is a problem which has not aroused much interest in those who may be qualified to solve it. Most likely, the success of the probabilistic model for dealing with the problem of randomness has left little choice in the matter.

c. The Probabilistic Model. The decision rules that will be presented here employ a "probabilistic model". Such a model contains basic axioms which are given in Attachment 1 of this document. It should be noted that the main feature of this general model is the assertion that a function P exists which gives the probability of an event E occurring for any event E that may occur. But what properties must the observed physical situation satisfy in order to justify this assertion? Most would agree that the following property is essential?

(i) That the data is (or may conceivably be) collected under a repetitive process, and is collected without bias. Thus, even if impractical to do so, one could continue the experiment indefinitely, and the selection of data does not depend on what occurs (that is, one cannot discard data "after the fact" as long as such data falls within our "space of events.")

Some would also insist that the following property must hold:

(ii) That the data must possess a so-called "statistical regularity" or "long-run stability". This property permits one to conceive of probability as a relative frequency, i.e., the (approximate) proportion of times that events will occur if the experiment is continued long enough.

Many believe that justification of property (ii) is not required in order to use the probabilistic model. They argue that experience shows that satisfying property (i) leads to a satisfaction of (ii). However, it would not be consistent with the purposes of this document to enter into this argument here.

d. Choosing the Probability Function P. There is usually insufficient time available to use decision-making techniques to determine the probability function (of a particular random variable) for each class of electronic equipment under consideration. Fortunately, there is a general agreement that the exponential density function describes the behavior of most electronic equipment reasonably well. This function takes the form $\frac{1}{\theta} e^{-(t/\theta)}$, where the random variable t denotes "operating-times-between-failures" and θ is the mean-time-between-failures (MTBF). By integrating this function from t to infinity we derive the familiar reliability function

$$R(t) = e^{-(t/\theta)}$$

which gives the probability of failure-free operation for time t. It is also widely known that in the exponential case, the random variable "quantities of failures for given test times" obeys a Poisson distribution with parameter θ:

$$P(x;\theta;t) = \frac{e^{-(t/\theta)}(t/\theta)^x}{x!}$$

yields the probability of exactly x failures occurring in test time t if the true MTBF, θ, is known.

Such wealth of information concerning the math model gives rise to certain advantages, not the least of which is simplicity. (Probably, the most important feature of a decision rule is that it be understood by the parties involved.) Other advantages, not usually encountered in statistical literature (since most authors seek more general results) are:

(1) More meaningful hypotheses are established.

(2) Producer and consumer risks may be explicitly quantified and evaluated.

(3) Procedures may be developed for comparing various accept/reject criteria, under a given set of conditions, through the use of probability of acceptance curves.

Before detailing specific decision rules, it is advisable to discuss some problems associated with establishing hypotheses as well as some considerations which dictate how the data is to be interpreted.

e. Establishing Hypotheses - The Interpretive Process. It was stated earlier that a scientific evaluation of data is dependent upon the choice of pertinent hypotheses to compare the data against. (In fact, the hypotheses will usually dictate the type of data to collect.) In reliability decision-making, additional assumptions are required which reflect the nature of the equipment and/or the requirements of the producer and consumer, so that rejection (acceptance) of the hypotheses means rejection (acceptance) of the equipment. These assumptions are not a part of the mathematical model, although they are made in consideration of it. Of course, they must be carefully scrutinized prior to the use of any decision rule, since the final decision rests heavily upon these assumptions. Hence, the main task of reliability decision-making is to make reasonable assumptions so that hypotheses may be established which will lead to accept/reject decisions which satisfy each of the parties involved. It shall be seen that both parties are largely concerned with the possibility that incorrect decisions will be made, i.e., the producer fears that satisfactory equipment may fail the test while the consumer fears that unsatisfactory equipment may pass the test. Therefore, an equitable solution would be the following interpretive process: (1) properly define "satisfactory" and "unsatisfactory"; (2) develop quantitative expressions (called risk functions) for the possibilities of making incorrect decisions; and, finally, (3) hold these expressions to a minimum when making accept/reject decisions (consistent of course with other practical constraints). This interpretive technique is used in each decision rule presented in the hope of satisfying both parties.

2. Specific Decision Rules. Generally speaking there are two approaches that shall be presented called "Fixed Time Tests" and "Sequential Tests". Their similarities and differences cannot be fully understood until the procedure of each rule is known. Hence, these procedures are presented first, and the next chapter shall be devoted to a comparative discussion.

Table I (next page) contains what may be called the "test logic" and provides justification for the rules of procedure that follow (except for certain proofs which are placed in the attachments to this pamphlet). The table should not be read superficially; rather, it should be studied carefully, one column at a time. The primary reason for placing this information in a table is to make the reader cognizant of similarities and differences of the various tests, as each one is studied. This results in a saving of time and effort; that is, having studied and understood an aspect of one test, the reader will not, unwittingly, dwell on this aspect again for a subsequent test. However, the reader who is studying this test logic for the first time, must be on guard to resist the temptation of studying two tests simultaneously. The mere adjacency of the statements makes this temptation ever-present; and, if not resisted, could result in something less than full understanding of any one test.

There are many other rules that may be devised; here, we have taken a few of the most popular ones and placed them all within the same framework. It is expected that most, if not all, decision rules may be fitted into this framework. An obvious advantage results from such an effort, namely, ease of communication between producer and consumer particularly when a new approach to decision-making is recommended. A possible disadvantage, of course, is that reasonable approaches may be disapproved because they do not admit to this framework; however, it is hoped that this disadvantage is superseded by the advantage of detecting unreasonable approaches (after they have been fitted to this framework).

Certain details of each of these techniques - in particular, proofs - have been placed in Attachments 2, 3, and 4. Definitions of terms and symbols are given in Attachments 5 and 6.

<table>
<tr><th></th><th>Column I</th><th>Column II</th><th>Column III</th><th>Column IV</th></tr>
<tr><th></th><th>PFTT (POISSON FIXED TIME TEST)</th><th>PFTT
(Alternate values of MTBF)</th><th>PST (POISSON SEQUENTIAL TEST)</th><th>PRST (PROBABILITY RATIO SEQUENTIAL TEST)</th></tr>
<tr><td>BASIC AXIOMS</td><td colspan="2">All Columns use probabilistic model and Poisson function:
$P_x = P(x;\theta;t) = \frac{e^{-U}\,U^x}{x!}$ $P\left\{\begin{array}{l}\text{exactly } x \text{ failures occurring}\\ \text{when } U = t/\theta \text{ is known}\end{array}\right\}$</td><td>See Columns I and II</td><td>See Columns I and II</td></tr>
<tr><td>THEOREMS</td><td colspan="2">All Columns derive $C_x = C(x;\theta;t) = \sum_{r=0}^{x} \frac{e^{-U}\,U^r}{r!} = P\left\{\begin{array}{l}x \text{ or fewer failures occur-}\\ \text{ring when } U = t/\theta \text{ is known}\end{array}\right\}$
and $D_x = D(x;\theta;t) = \begin{pmatrix} 1 - C_{x-1}, & \text{if } x \geq 1 \\ 1 & , \text{if } x = 0 \end{pmatrix} = P\left\{\begin{array}{l}x \text{ or more failures occurring}\\ \text{when } U = t/\theta \text{ is known}\end{array}\right\}$
by direct application of basic laws of probability theory (Attachment 1).</td><td>See Columns I and II</td><td>In addition to Columns I and II, if $x_1 + x_2 + \ldots + x_r = n$ and if we let $rt' = t$, then the ratio
$R = \frac{L(x_1, x_2, \ldots, x_r; \theta_1; t')}{L(x_1, x_2, \ldots, x_r; \theta_0; t')} = \frac{P(n;\theta_1;t)}{P(n;\theta_0;t)}$
where $L(x_1, x_2, \ldots, x_r; \theta; t')$ denotes the probability of having exactly x_i $(i = 1, 2, \ldots, r)$ failures in each of the r successive time intervals of length t'. (See Attachment 3 for proof).</td></tr>
<tr><td>DATA</td><td colspan="2">For Columns I and II, equipments tested for length of operating time t and N_t, the number of failures that occur in time t, shall be recorded.</td><td colspan="2">For Columns III and IV equipments are tested and as each failure occurs, the times at which they occur are recorded.</td></tr>
<tr><td>HYPOTHESES</td><td>Having tested for total operating time t, decide whether or not $\theta \geq \theta^*$, where θ^* is a specified value.</td><td>See Columns III and IV</td><td colspan="2">For Columns II, III, and IV, at each occurrence of a failure decide whether $\theta \geq \theta_0$ or $\theta \leq \theta_1$ where θ_0 and θ_1 are specified values and $\theta_0 > \theta_1$. If a decision is not possible, continue testing to the next failure.</td></tr>
<tr><td>ASSUMPTIONS</td><td>The above hypothesis requires that the following assumptions be made:
1. That consumer requires equipment with true MTBF $\geq \theta^*$, and this value may be specified.
2. Equipments with true MTBF $< \theta^*$ are considered unsatisfactory.
3. The true value of MTBF is fixed by the design and a value θ^* is attainable.
4. There are only two ways of making an incorrect decision, whatever criteria is adopted. These are (1) Rejecting "$\theta \geq \theta^*$ is true" when it is actually true, or (2) Rejecting "$\theta < \theta^*$ is true" when it is actually true.</td><td>See Columns III and IV</td><td colspan="2">For Columns II, III, and IV, the above hypothesis requires that the following assertions be made:
1. That consumer desires equipment with true MTBF greater than or equal to θ_0, and this value may be specified beforehand.
2. That a value θ_1 (less than θ_0) may be specified such that values of true MTBF less than or equal to θ_1 are considered unsatisfactory.
3. That values of θ such that $\theta_1 < \theta < \theta_0$ are neither satisfactory nor unsatisfactory. In fact, it must be <u>theoretically</u> assumed that such values are not possible so that rejection of $\theta \geq \theta_0$ means acceptance of $\theta \leq \theta_1$.
4. That the true value of MTBF is fixed by the design and a value θ_0 is attainable.
5. There are only two ways of making an incorrect decision, whatever criteria is adopted. These are: (1) Rejecting "$\theta \geq \theta_0$ is true" when it is actually true, or (2) Rejecting "$\theta \leq \theta_1$ is true" when it is actually true.</td></tr>
<tr><td>INTERPRETIVE TECHNIQUES</td><td colspan="2">Steps which appear below apply to all Columns except that for Column I, $\theta_0 = \theta_1 = \theta^*$, and for Columns I and II, $m_1 = m_0 - 1$.
1. Define "producer risk", α, as follows: $\alpha = P\{$satisfactory equipment will be rejected$\} = P\{$rejecting "$\theta \geq \theta_0$ is true" when it is true$\} = P\{N_t \geq m_0 \mid \theta \geq \theta_0\}$, where θ_0 is a fixed, known value, θ is a fixed, unknown value, and m_1 is the number of failures specified for rejection. (For Column I only, change "$\theta \geq \theta_0$" to "$\theta \geq \theta^*$".)
2. Define "consumer risk", β, as follows: $\beta = P\{$unsatisfactory equipment will be accepted$\} = P\{$rejecting "$\theta \leq \theta_1$ is true" when it is true$\} = P\{N_t \leq m_1 \mid \theta \leq \theta_1\}$ where θ_1 is a fixed, known value, θ is a fixed, unknown value, and m_1 is the number of failures specified for acceptance. (For Column I only, change "$\theta \leq \theta_1$" to "$\theta < \theta^*$" and change m_1 to $m_0 - 1$)
3. Since θ is unknown, the exact determination of α and β is difficult, However, it can be shown (Attachment 2) that α and β are bounded above by $D(m_0;\theta_0;t)$ and $C(m_1;\theta_1;t)$; that is, $\alpha \leq D(m_0;\theta_0;t)$, $\beta \leq C(m_1;\theta_1;t)$. Further, no smaller bounds may be found for these risks since θ remains unknown. Thus, assuming equality instead of inequality gives us a "worst case" figure for the risks. (For Col I, change θ_0 and θ_1 to θ^* and change m_1 to $m_0 - 1$).</td><td>See Columns I and II</td><td>In addition to steps in Column I and II, we consider that if $R > 1$, then the probability of obtaining exactly n failures in time t is greater under the assumption that θ_1 is true than it is under the assumption that θ_0 is true; hence, we tend to believe that $\theta = \theta_1$. Similarly, if $R < 1$ we tend to believe that $\theta = \theta_0$. In fact, it can be shown that the true risks α and β, as defined above, will not be violated if we "reject $\theta \geq \theta_0$ is true" when $R \geq \frac{1-\beta}{\alpha}$ and reject "$\theta \leq \theta_1$ is true" when $R \leq \frac{\beta}{1-\alpha}$.</td></tr>
</table>

a. **Fixed Time Tests**. Actually, all rules to be considered here require a fixed amount of testing, so that one may be puzzled by the name "Fixed Time Test". The reason for this name is that the rule specifies the exact duration of testing with no intermediate decision points. When this amount of (operating) time has elapsed, a decision either to accept or reject will be made based upon the number of failures that have occurred. It follows, then, that the number of failures which cause an accept decision must be one less than the number of failures which require a reject decision. (It will be seen later that Sequential Tests operate much differently). Definitions and explanations of symbols used to explain the various tests can be obtained by consulting Attachments 5 and 6.

(1) POISSON FIXED TIME TEST (PFTT)

The rule of procedure (decision criteria) is as follows:

Step I: Choose

(a) MTBF requirement, say θ^*.

(b) Test time, t.

(c) Consumer's risk, β.

Step II: Using tables of the Poisson Distribution (see ESDP 80-5) find acceptance number x which satisfies:

$$C(x;\theta^*;t) = \beta$$

NOTE: In this rule, the rejection number is x + 1 and the producer's risk, α, is at most $1 - \beta$ since $D(x + 1;\theta^*;t) = 1 - \beta$

EXAMPLE: Let $\theta^* = 100$, $t = 170$, and, $\beta = 50\%$, then if

$$x = 1$$

$$C(x;\theta^*;t) = C(1;100;170)$$

$$= .497$$

$$= \beta \quad \text{(approximately)}$$

Hence, we may accept if $N_t = N_{170} \leq 1$, without violating the consumer's risk, β. Of course, in this case, the producer's risk, α, may be as high as

$$D(x + 1;\theta^*;t) = D(2;100;170)$$

$$= .503$$

$$\text{or } 50\% \quad \text{(approximately)}$$

NOTE: This example assumed that only 170 hours were available for test; but if 100n + 70 were available (for n = 0, 1, 2, ...) one can choose x = n and still maintain risks of 50% for both parties.

(2) PFTT (Alternate Values of MTBF)

The high risk levels required by the PFTT where both risks are evaluated using one value of θ, can be alleviated by basing such risks on alternate values of θ, say θ_0 and θ_1. The philosophy behind this maneuver is simply that it does not seem reasonable that the consumer requires MTBF = $\theta^* = \theta_0$ and values slightly below θ_0 are deemed unsatisfactory. It is more likely that a value of MTBF exists which is less than θ_0 say θ_1, such that if $\theta \leq \theta_1$, operational effectiveness would seriously deteriorate. Therefore, this lower value θ_1 is determined in advance and the consumer's risk, β, is evaluated using θ_1 while the producer's risk, α, is computed using the value θ_0. This has the effect of establishing a "zone of indifference", namely, those values of θ between θ_1 and θ_0. Although values of MTBF falling within this zone are not deemed "satisfactory" neither are they deemed "unsatisfactory", and the probability of accepting such equipments is permitted to rise higher than the predetermined risk level, β. Also, the probability of rejecting such equipments is permitted to rise higher than the predetermined risk level, α. A special feature of this technique is that for given values of α and β, as the size of the zone of indifference increases, the required test time t decreases. Much of what follows is a repetition of the PFTT procedure with certain modifications.

Step I: Choose

(a) MTBF upper and lower bound values, θ_0 and θ_1.

(b) Test time, t.

(c) Consumer's risk, β.

Step II: Using tables of the Poisson Distribution (see ESDP 80-5) find acceptance number x which satisfies

$$C(x;\theta_1;t) = \beta$$

NOTE: In this rule, the rejection number is x + 1, but the producer's risk, α is not as high as $1 - \beta$ since $D(x + 1;\theta_0;t)$; that is, β is computed using θ_1 and the "worst case" figure for α is computed using θ_0.

EXAMPLE: Let $\theta_0 = 200$, $\theta_1 = 100$, $t = 2{,}000$, $\beta = 10\%$, then $x = 14$ yields:

$$C(x;\theta_1;t) = C(14;100;2{,}000) = .105 = \beta. \quad \text{(approximately)}$$

Hence, we may accept if $N_t = N_{2,000} = 14$ without violating the consumer's risk, β. In this case, the producer's risk, α, is at most

$$D(x + 1;\theta_o;t)$$

$$= D(15;200;2,000)$$

$$\doteq .083,$$

or 8% approximately.

b. Sequential Tests. In fixed-time tests an accept decision is not possible until the prescribed test time has been completed. In the last example, for instance, the decision was to accept if 14 or lees failures occurred in 2,000 hours of testing. Now, suppose that after 1,000 houre of testing zero failures had occurred. One might suspect that the consumer could accept at this point with a low riek. The risk, in fact, would be $C(0;100;1,000) = .000045$ (less than one ten-thousandths of one percent!) Considerations such as these lead to the concept of "sequential testing." This concept can be stated eimply as follows: Develop procedures which would permit decisions at such (earlier) times without violating the pre-selected risk levele.

Two types of sequential tests shall be presented. These are called (1) Probability Ratio Sequential Test (PRST)[1] and (2) Poisson Sequential Test (PST).

(1) PROBABILITY RATIO SEQUENTIAL TEST (PRST).

The rule of procedure (decision criteria) is as follows:

Step (1): Choose

(a) MTBF upper and lower bound values, θ_o and θ_1.

(b) Consumer's risk, β.

(c) Producer's risk, α.

1 For a more general discussion of the PRST see Wald's "Sequential Analysis" published by John Wiley & Sons, Chapman and Hall Ltd. London (1947). See also, Attachment 3.

Step (2): For successive numbers of failures $i = 0,1,2,\ldots$, etc., solve the following equations for t_i and t_j:

$$t_i = \left(\frac{\theta_o}{1 - d}\right)\left[\ln\left(\frac{\beta}{1 - \alpha}\right) - i(\ln d)\right]$$

$$t_j = \left(\frac{\theta_o}{1 - d}\right)\left[\ln\left(\frac{1 - \beta}{\alpha}\right) - j(\ln d)\right]$$

where the derived t_i's represent minimum test times for acceptance if i or less failures have occurred, and the derived t_j's represent maximum test times for rejection if j or more failures have occurred. (See Attachment 3 for derivation of formulas for t_i and t_j, above).

Step (3): Truncation. To prevent this test from continuing to undesirable lengthe, the following truncation procedure may be used: Scanning tables of the Poieson Distribution find a number x such that

$C(x;\theta_1;t) \leq \beta$.

and $D(x;\theta_o;t) = \alpha$.

This is always possible because of the fact that the formulas for t_i and t_j, given in Step (2), yield accept/reject times which hold the true risks somewhat below α and β.[1]

In Chapter IV a specific test ehall be derived using the PRST technique and an analysis of the actual risks shall be made. It will become apparent that the PRST holds the risks lower than originally intended.

This is the result of using the approximations $\frac{1 - \beta}{\alpha}$ and $\frac{\beta}{1 - \alpha}$ for constante A and B, and the effect is that a longer test duration is required. In fact, if MTBFs are high (say, in the order of 500 hours or more) the cost of testing and the consequences of delayed decisions makee the PRST techniquss prohibitive. This is especially eo if the true MTBF of the equipment falls in the zone of indifference (between θ_1 and θ_o).

The following technique attempts to combine certain advantages of the PFTT and the PRST while removing certain dieadvantages in order to cope with the above stated situation. These advantages and dieadvantagee shall be discussed in Chapter IV.

1 Justification for this method need not be explained (again) because of its similarity with the PFTT (Alternate Values of MTBF).

(2) POISSON SEQUENTIAL TEST (PST).

The rule of procedure (decision criteria) is as follows:

Step (1): Choose

(a) MTBF upper and lower bound values, θ_o and θ_1.

(b) Consumer's risk, β.

(c) Producer's risk, α.

Step (2): Using tables of the Poisson Distribution starting with small values of $U_i = t_{i}/\theta_1$, find the first point t_i at which

$C(i;\theta_1;t_1) = \beta$ (for $i = 0,1,2,\ldots$,etc)

That is, derive $U_o = t_o/\theta_1$ that corresponds with $C(0;\theta_1;t_o) = \beta$, then $U_1 = t_1/\theta_1$ that corresponds with $C(1;\theta_1;t_1) = \beta$, and so on. Then solve each of the equations $U_i = t_i/\theta_1$ for t_i to obtain $t_o, t_1, \ldots$,etc., where each t_i represents minimum allowable test time for acceptance if i or less failures have occurred in that time.

Step (3): Follow exactly the same procedure as Step (2) using α, θ_o, and $D(x;\theta_o;t_j)$ to derive t_j's where each t_j is maximum allowable test time for rejection if j or more failures have occurred by that time.

Step (4): Truncation. This test will terminate itself automatically, i.e., eventually a point will be reached where $t_i = t_j$ and $i = j - 1$ (the number of failures for an accept decision is one less than the number of failures for a reject decision) However, the test may be truncated much earlier as a result of considerations which are given in Attachment 4 , to this pamphlet.

Chapter 4

COMPARATIVE ANALYSIS - CONSTRUCTION AND APPLICATION OF PROBABILITY OF ACCEPTANCE CURVES

1. **The Basic Tools:**
Each of the preceding decision rules employed the probabilistic model using the Poisson frequency function as the probability function P, that is:

$$P(x;\theta;t) = \frac{e^{-U}U^x}{x!} = \left\{\begin{array}{l}\text{The probability of exactly x failures}\\ \text{occurring when } U = t/\theta \text{ is known}\end{array}\right\}$$

where t is the operating time and θ is the true MTBF of the equipment. The following formulae may be derived from $P(x;\theta;t)$ using basic axioms of probability theory (see Attachment 1):

$$C(x;\theta;t) = \sum_{r=0}^{x} \frac{e^{-U}U^r}{r!} = \left\{\begin{array}{l}\text{The probability of x of fewer failures}\\ \text{occurring when } U = t/\theta \text{ is known}\end{array}\right\}$$

$$D(x;\theta;t) = \begin{pmatrix} 1 - C(x-1), & \text{if } x \geq 1 \\ 1 & \text{, if } x = 0 \end{pmatrix} = \left\{\begin{array}{l}\text{The probability of x or}\\ \text{more failures occurring}\\ \text{when } U = t/\theta \text{ is known}\end{array}\right\}$$

To determine the probability of failure-free operation for time t, it suffices to calculate

$$P(0;\theta;t) = \frac{e^{-t/\theta}(t/\theta)^0}{0!} = e^{-t/\theta}$$

which is considered to be the reliability function, R(t). Thus knowledge of θ is equivalent to knowledge of the equipment reliability (for given test times.)

A technique may now be given for analyzing the differences in these decision rules. Before doing so, however, it is convenient to discuss the features of Fixed Time Tests as opposed to Sequential Tests.

2. Fixed Time Tests versus Sequential Tests. For ease of discussion, the following comments are directed towards comparing the PFTT (Alternate values of MTBF) and the PST, since these rules differ only in that the former assumes a "fixed time" approach whereas the latter assumes a "sequential" approach. The fixed time approach considers that the amount of time t that may be allotted for reliability testing is extremely limited so that achieving more than one failure in this time is rather

unlikely. Hence, imputs of Θ_1, Θ_0, fixed time t, producer and consumer risks are combined to determine maximum quantities of failures for acceptance and minimum quantities of failures for rejection (which, naturally, differ by one), in the given time t. Diagramatically

INPUTS		OUTPUTS
$\Theta_0, \Theta_1, \alpha, \beta, t$	$\longrightarrow$	Accept if # failures $\leq x$ Reject if # failures $\geq x + 1$

Occasionally risks may require adjustment (upwards) because the test time is so limited.

On the other hand, in the sequential approach, test time is more flexible (though not any less important). Thus, inputs of Θ_1,Θ_0, producer and consumer risks are combined with successive numbers of failures 0, 1, 2, and so on, to determine minimum test times for acceptance and maximum test times for rejection to be associated with each of these numbers of failures:

INPUTS		OUTPUTS
$\Theta_0, \Theta_1, \alpha, \beta$, and consecutive # of failures 0,1,2, etc.	$\longrightarrow$	Test times for Accept Test times for Reject

(Other procedures are used to find a point for truncation without violating the prescribed risks.) Occasionally, when high MTBF's are involved, the amount of total test time becomes unreasonable unless the risks are adjusted (upwards). However, this adjustment is not as severe as in the case of the fixed time approach.

Essentially, then, the sequential approach is merely a series of fixed time tests except that certain test times may have acceptance numbers only and <u>other</u> test times may have rejection numbers only. The test ends, of course, when an acceptance time coincides with a rejection time and the quantity of failures permitted at that acceptance time is one less than that permitted at the rejection time.

Consequently, there is little need to discuss the conditions which make the fixed time test preferable to the sequential test. The answer is: Use the sequential test whenever the allotted test time permits; when time is insufficient, resort to the fixed time test.

3. <u>PRST versus PST</u>. Let us now assume that time is rather flexible (but by no means unlimited!). Our problem then reduces to choosing between the PRST and PST. It shall turn out that the key consideration is again that of the amount of time that may reasonably be allotted to

reliability testing. To see this more clearly, suppose that the following conditions apply:

Θ_0 = 600 hours = Satisfactory value of MTBF

Θ_1 = 400 hours = Unsatisfactory value of MTBF

α = 20% = P{Satisfactory equipment will be rejected}

β = 20% = P{Unsatisfactory equipment will be accepted}

Use of PRST technique as given in paragraph 2 of Chapter 3 yields the following accept/reject criteria:

<u>PRST ACCEPT/REJECT CRITERIA</u>

Risk Level $\leq$ 20% Discrimination Ratio: $3/2 = \Theta_0/\Theta_1$

Total observed failures	Reject (Equal or less) Total test time*	Accept (Equal or more) Total test time*
0	N/A	2.8
1	N/A	3.6
2	N/A	4.4
3	N/A	5.2
4	0.5	6.0
5	1.3	6.8
6	2.1	7.6
7	2.9	8.5
8	3.7	9.3
9	4.5	10.1
10	5.3	10.9
11	6.1	11.7
12	6.9	12.5
13	7.7	13.3
14	8.6	14.1
15	9.4	14.6
16	10.2	14.6
17	11.0	14.6
18	11.8	14.6
19	14.6	N/A

*Total test time is expressed in multiples of Θ_0

There is nothing to stop equipments from remaining in the continue test region for the entire span of the test. In other words, there is a distinct possibility of the test lasting 14.6 multiples of Θ_0 or 14.6 x 600 = 8,760 hours. Even if two models were simultaneously tested

with their test times and quantities of failures combined, this would require 4,380 test hours or more than 6 months of 24-hour-a-day reliability testing!

Now consider use of the PST technique as given in Chapter 3. Following that procedure yields the following accept/reject criteria:

PST ACCEPT/REJECT CRITERIA

Risk Level = 20% Discrimination Ratio: $3/2 = \theta_o/\theta_1$

Total observed failures	Total test time* for REJECT (equal or less)	Total test time* for ACCEPT (equal or more)
0	N/A	1.60
1	N/A	3.00
2	N/A	3.45
3	2.30	3.45
4	3.45	N/A

*Total test time is expressed in multiples of θ_1.

Here, maximum test time is 3.45 multiples of θ or $(3.45) \times 400 = 1,380$. If, again, two models could be tested simultaneously, the number of test hours required would be (at most) 690, or less than one month!

A reasonable question, at this point, is: How can both the PRST and the PST criteria be based on the same risks ($\alpha = \beta = 20\%$) and the same discrimination ratio $(d = \theta_o/\theta_1 = 600/400 = 3/2)$ and yet yield such differing criteria? Part of the answer is simply that the PRST does not use the risk functions

$$\alpha = P\{N_t \geq n_1 \mid \theta = \theta_o\}$$
$$\beta = P\{N_t \leq n_1 \mid \theta = \theta_1\}$$

directly to derive the accept/reject criteria, whereas the PST does. Hence, the PST allows α and β to reach these levels, but the PRST keeps the risks well below these levels. The rest of the answer is supplied by the fact that the PRST does not use previously gained information in order to find a point for truncation whereas the PST does.

Another question that may be raised is: Why, then, do we need the PRST--why not simply utilize the PST as the decision rule, since it makes decisions which are consistent with the predetermined risk levels and does so in less time?

The answer is furnished by looking at "probability of acceptance curves" for each of these tests. Such curves are constructed as follows:

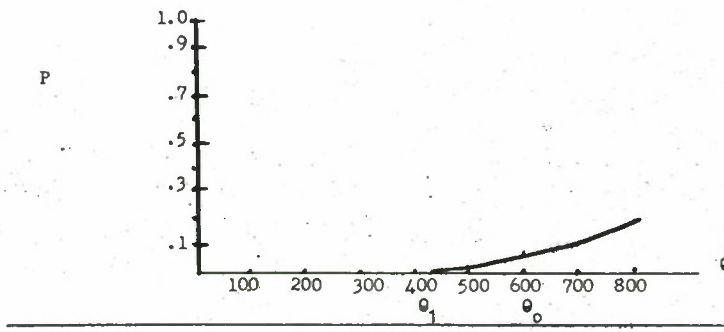
At any decision point of the PRST or PST, one may plot, as a function of θ, the following:

$$P\{a \text{ or less failures occur in time } t^* \mid \theta\}$$

$$= \sum_{r=0}^{a} \frac{e^{-t^*/\theta}(t^*/\theta)^r}{r!}$$

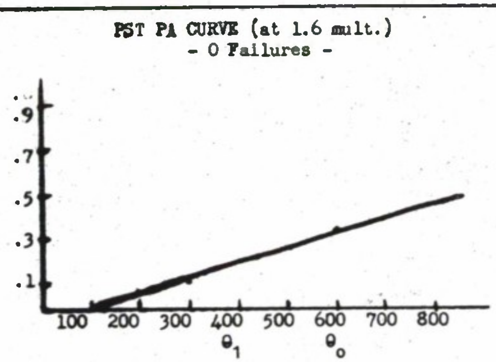
where a is the number of failures specified for acceptance at decision point t^*. Evidently, this expression gives the probability of acceptance as a function of the true MTBF θ. Looking at the first decision point of the PRST previously derived gives

PRST PA CURVE (at 2.8 multiples of θ_o)
- 0 Failures -



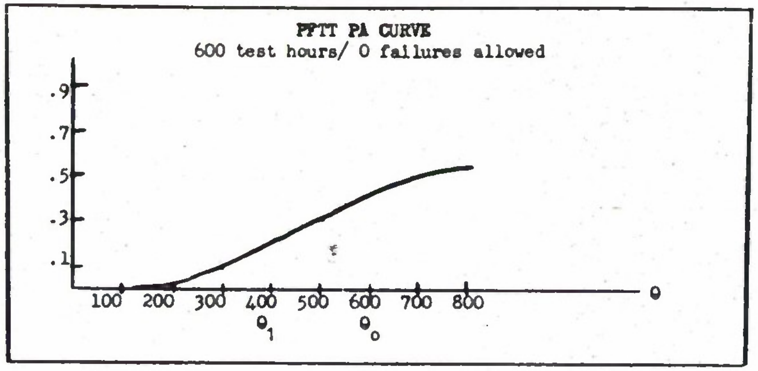
This curve shows quite clearly that the PRST holds the risks much lower than originally intended at earlier decision points.

Plotting this same function for the first decision point of the PST which was derived gives:



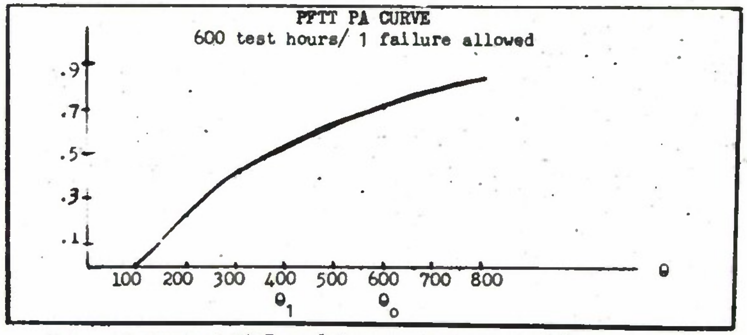
Note that for values of MTBF less than or equal to 400 hours, the probability of acceptance is below 20%. But there is a significant area under the curve to the left of the 400 hour point, whereas the PRST has not. It is clear then, that the PRST provides better protection against accepting unsatisfactory equipments, since a similar situation holds at any decision point that is plotted.

4. PA Curves for Fixed Time Tests. Now suppose that the MTBF, the number of models available for test, and operational commitments are such that even the PST provides too long a test. For the case previously considered, suppose that only one model was available, causing possible test duration of 1,380 hours (about two months) which is too long. Suppose further that only 600 hours of testing could be permitted. Again PA curves could be used to choose the most appropriate Fixed Time decision rule. For example, if 0 failures is specified as acceptance number (here, 1 failure is the rejection number) the PA curve takes the form



It should be observed that since the rejection number is one more than the acceptance number, the probability of rejection is "one minus the probability of acceptance". (This does not hold for sequential tests, however.) Thus, this curve shows that if the true MTBF is 800 hours (200 more than required), there is better than a 50% probability of rejection, since there is only a 47% chance of acceptance.

Changing the acceptance number to 1 (the rejection number to 2) produces a rather striking change to the PA Curve, as shown below:



Here, if the true MTBF is 800 hours there is an 82% chance of acceptance. But now, there is a 40% chance that equipment with 300 hours MTBF (300 less than required) would pass the test. Clearly one must choose either 0 or 1 as the acceptance number, and this is a formidable task, since there is considerable difficulty in holding both Air Force and producer risks at low levels.

5. Advantages and Disadvantages. As a result of analyzing PA curves for the three kinds of tests, it is possible to summarize certain conclusions in terms of advantages and disadvantages of using each of these techniques. These are tabulated on the following pages.

PFTT ADVANTAGES

1. Test is simple to administer—equations are available which permit specification of the accept/reject criteria in terms of MTBF requirements.

2. Permits specification of risks before testing begins.

3. The exact test time is known in advance and may be scheduled and costed.

4. Possible to devise criteria to fit most any IOC date.

5. If producer has designed equipment with MTBF much higher than required, he may be willing to assume much higher risk, thus shortening test time considerably.

PRST ADVANTAGES

1. Permits earlier decisions for equipments extremely better or extremely worse than required.

2. The test is simple to administer—equations are available which permit specification of the accept/reject criteria in terms of MTBF requirements.

3. Has intuitive appeal as a result of using the "Likelihood function" (in addition to risk levels) as a basis for deriving accept/reject criteria.

4. Permits specification of risks (consumer's and producer's) before testing begins. (However, for risks above certain levels, the approximations used to derive the PRST are no longer valid.)

PST ADVANTAGES

1. Test is simple to administer—equations are available which permit specification of the accept/reject criteria in terms of MTBF requirements.

2. Permits earlier decisions for satisfactory or unsatisfactory equipments.

3. Permits earlier truncation of testing as a result of utilizing the fact that the equipment was not accepted or rejected at previous decision points.

4. Permits specification of risks before testing begins.

5. Possible to devise criteria to fit most any IOC date. (However, if test duration is shortened too much, the PST reduces to the PFTT.)

6. If producer has designed equipment with MTBF much higher than required, he may be willing to assume much higher risk thus shortening test time considerably.

7. Although the exact test time is not known in advance, the entire span of the test is short (as compared with PRST), and good approximations of test duration can be made for purposes of costing and scheduling the test.

PFTT DISADVANTAGES

1. Has little intuitive appeal since the accept/reject criteria is based solely upon the risks involved.

2. If only one value of MTBF is specified, one of the risks is the complement of the other; that is, if the consumer's risk is 10%, the producer's risk is 90%. Thus, one party or both parties must assume a high degree of risk. (This can be partially alleviated by specifying upper and lower bound values.)

PRST DISADVANTAGES

1. The test logic is concerned with testing one value of MTBF against another. Thus, a discrimination ratio must be selected; that is, MTBF upper and lower bound values must be decided upon.

2. Requires excessive test time for equipments whose true MTBF falls within the "zone of indifference" (values between the upper and lower bound values), although such equipments are not deemed unsatisfactory.

3. The true risks (consumer's and producer's) usually are held much lower than those agreed upon before testing began, thereby causing excessive test time. When risks of 10% or more are initially prescribed, the test holds the risks at 7% or more below these values.

4. Formulas exist for evaluating expected test time, but as a function of the true MTBF which is unknown; hence, scheduling and costing this test is difficult. In certain cases, fear of having to run the entire span may cause the test to be waived.

5. Extremely difficult to devise tests to fit early IOC dates.

6. The procedure for truncation does not utilize information concerning the performance of equipment at previous decision points, which results in unnecessary testing.

PST DISADVANTAGES

1. Has little intuitive appeal since the accept/reject criteria is based solely upon the risks involved.

2. The test logic is concerned with testing one value of MTBF against another. Thus, a discrimination ratio must be selected; that is, MTBF upper and lower bound values must be decided upon.

Chapter 5

SUMMARY AND CONCLUSIONS

1. The preceding chapters have attempted to provide a framework for various Reliability decision-making techniques in order to develop a rationale for choosing appropriate statistical accept/reject criteria. Specifically the following points were emphasized.

a. That no one decision rule can be applied to all procurements.

b. That meaningful requirements cannot be established without consideration of the available methods (decision rules) for assuring that such requirements are satisfied. For example, the sequential test methods that were presented here required that MTBF upper and lower bound values be stipulated.

c. That any decision rule carries with it certain risks for both consumer and producer as a result of the fact that only a small portion of the time domain (useful life) will be sampled during the demonstration. Thus, risk levels must be decided upon before the demonstration begins.

d. That risk levels cannot be chosen without considering certain aspects of the procurement situation such as schedules, cost of testing, etc., all of which affect the amount of time that may be devoted to reliability testing. Neither should a "time allotment" determination be made without considering the effect upon risk levels.

e. That if sufficient time is allotted, "sequential tests" are preferred over "fixed time tests" because they make possible earlier decisions without violating the prescribed risks.

2. An important and strongly related topic was avoided in this discussion, namely, the meaning (consequences) of accept-reject decisions. Besides the fact that such considerations go beyond what we set out to accomplish, such related topics as "incentives", "penalties", etc., would be involved, and would probably serve to distract the reader from our intended purposes. Moreover, it is expected that other documents will give adequate coverage to this important topic.

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ATTACHMENTS 1 THROUGH 6

RELIABILITY DECISION MAKING

CONSTRUCTION AND APPLICATION

OF

PROBABILITY OF ACCEPTANCE CURVES

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BASIC LAWS OF PROBABILITY

1. Underlying Assumption. The elements of set theory, wherein a point (element) is called an "outcome of an experiment", the collection of all points (outcomes) is called the "sample space" (and denoted by G), and any sub-collection of points (outcomes) of G is called an "event". In particular G is an event, and the collection consisting of no points (outcomes) is an event (called the "null event" and denoted by $\emptyset$). A "random variable" is a numerical - valued function defined over the sample space G; i.e., a rule which assigns exactly one number to each outcome. We write "$w \in G$" when we mean "w is an element of G."

2. Basic Axioms. We assume the existence of a function P satisfying the following axioms[1].

a. Axiom 1: $P\{G\} = 1$

b. Axiom 2: $P\{\emptyset\} = 0$

c. Axiom 3: $0 \leq P\{E\} \leq 1$ for any event E

d. Axiom 4: $P\{E_1 \cup E_2\} = P\{E_1\} + P\{E_2\} - P\{E_1 \cap E_2\}$

NOTE: If $\{E_1 \cap E_2\} = \{\emptyset\}$ then

$$P\{E_1 \cup E_2\} = P\{E_1\} + P\{E_2\}$$

3. Cumulative Distribution Function. For any random variable $X = X(w)$ the function defined by

$$F_X : F_X(a) = P\{X(w) \leq a\} \text{ where } (-\infty < a < \infty) \text{ and } w \in G, \text{ is}$$

called the cumulative distribution function.

4. Properties of the Cumulative Distribution Function. The cumulative distribution function has the following basic properties:

a. It is a non-decreasing function.

b. $F_X(-\infty) = 0$

c. $F_X(\infty) = 1$

[1] $P\{E\}$ is notation for "The (numerical) probability of the event E occurring". $\{E_1 \cap E_2\}$ signifies the simultaneous occurrence of E_1 and E_2. $\{E_1 \cup E_2\}$ is an event which occurs when either E_1 or E_2 occurs.

DERIVATION OF POISSON FIXED TIME TEST (PFTT) AND POISSON SEQUENTIAL TEST (PST)

1. PFTT:

a. Definition of consumer and producer risks; Let the producer risk, α, be defined by

$$\alpha = P\{\text{satisfactory equipment will be rejected}\}$$

and let the consumer risk, β, be defined by

$$\beta = P\{\text{unsatisfactory equipment will be accepted}\}$$

where "satisfactory equipment" is defined as equipment with true MTBF greater than or equal to θ^*, and "unsatisfactory equipment" is defined as equipment with true MTBF less than θ^*.

b. Quantification of consumer and producer risks: If equipments are tested for length of operating time t, and if accept/reject decisions are made based on N_t, the number of failures that occur in time t, then assuming that m failures occur, the quantity

$$P\{N_t \geq m \mid \theta \geq \theta^*\}$$

gives the producer's risk, α, if a reject decision is made; and, the quantity

$$P\{N_t \leq m \mid \theta < \theta^*\}$$

gives the consumer's risk, β, if an accept decision is made. In these expressions, θ^* is assumed fixed and known, whereas θ is assumed fixed but unknown.

c. Evaluation of consumer and producer risks: In spite of having developed expressions (in paragraph b, above) which seemingly quantify the risks, exact evaluation of these expressions is impossible because θ, the true MTBF, remains unknown. (We have no desire to treat θ as a random variable). However, if we assume that the random variable "quantities of failures for given test times" obeys a Poisson distribution with parameter θ, that is,

$$C(x;\theta;t) = \sum_{r=0}^{x} \frac{e^{-U} U^r}{r!} = P\{N_t \leq x, \text{ if } U = t/\theta \text{ is known}\}$$

$$D(x;\theta;t) = \begin{pmatrix} 1 - C_{x-1}, & \text{if } x \geq 1 \\ 1 & , \text{if } x = 0 \end{pmatrix} = P\{N_t \geq x, \text{ if } U = t/\theta \text{ is known}\}$$

then upper bounds may be found for α and β. This is accomplished as follows:

Consider the expressions

$$\alpha' = P_{lub}\left\{N_t \geq m \middle| \theta^-\right\}$$

$$\beta' = P_{lub}\left\{N_t \leq m \middle| \theta_-\right\}$$

where θ^- and θ_- denote that θ varies, (<u>not</u> randomly), but θ^- means that θ is restricted to values greater than or equal to θ^* and θ_- means that θ is restricted to values less than θ^*. (P_{lub} denotes the least upper bound[1] of the probabilities obtained as θ assumes any of the values indicated). Obviously α and β, as defined in paragraph b, above, are less than or equal to α' and β', respectively, (simply by the definition of "least upper bound".) Also, by scanning tables of the Poisson distribution (see ESDP 80-5) it is obvious that for fixed x and t, as θ <u>decreases</u>, $C(x;\theta;t)$ decreases, and as θ <u>increases</u>, $D(x;\theta;t)$ decreases. Thus we have shown that

$\alpha \leq \alpha' = D(m;\theta^*;t)$, if a <u>reject</u> decision is made on the basis of $N_t=m$.

$\beta \leq \beta' = C(m;\theta^*;t)$, if an <u>accept</u> decision is made on the basis of $N_t=m$.

In words, we have shown that evaluating $D(m;\theta;t)$ using $\theta = \theta^*$ gives a "worst case" probability for the producer's risk, α. Similarly $C(m;\theta^*;t)$ is a "worst case" probability for the consumer's risk, β. But no smaller bounds may be found for α and β since θ remains unknown.

d. <u>The PFTT Technique</u>: See page 22 of this document.

1. The "least upper bound" of a set of numbers is [illegible] greater than or equal to any number in the set. (It may or may not belong to the set).

2. PFTT (Alternate values of MTBF) and PST.

a. Same as 1.a, above, except that "satisfactory equipment" is defined as equipment with true MTBF greater than or equal to θ_o and "unsatisfactory equipment" is defined as equipment with true MTBF less than or equal to θ_1, where $\theta_1 < \theta_o$.

b. Same as 1.b, above, except that the producer's risk, α, is given by

$$P\left\{N_t \geq m \middle| \theta \geq \theta_o\right\}$$

and the consumer's risk, β, is given by

$$P\left\{N_t \leq m \middle| \theta \leq \theta_1\right\}$$

c. Same as 1.c, above, except that θ^- means that θ is restricted to values greater than or equal to θ_o and θ_- means that θ is restricted to values less than or equal to θ_1. Using the same argument, we are able to show that

$\alpha \leq \alpha' = D(m;\theta_o;t)$, if a reject decision is made on the basis of $N_t=m$

$\beta \leq \beta' = C(m;\theta_1;t)$, if an accept decision is made on the basis of $N_t=m$

Thus, evaluating $D(m;\theta;t)$ using $\theta = \theta_o$ gives a "worst case" probability for the producer's risk, α. Similarly, $C(m;\theta_1;t)$ is a "worst case" probability for the consumer's risk, β. Since θ remains unknown, no smaller bounds may be found for α and β.

d. <u>The PFTT Technique Using Alternate Values of MTBF</u>.

See page 23 of this document.

e. <u>The PST Technique</u>.

See page 26 of this document.

PROOF: Let $U_i = \frac{t'}{\theta_i}$ for $i = 0, 1$. Then

$$R = \frac{L(x_1, x_2, \ldots, x_r; \theta_1; t')}{L(x_1, x_2, \ldots, x_r; \theta_0; t')}$$

$$= \frac{e^{-rU_1} U_1^{\sum_{i=1}^{r} x_i} \Big/ \prod_{i=1}^{r} x_i!}{e^{-rU_0} U_0^{\sum_{i=1}^{r} x_i} \Big/ \prod_{i=1}^{r} x_i!} \qquad \text{(See para 1, above.)}$$

$$= \frac{e^{-rU_1} U_1^{\sum_{i=1}^{r} x_i}}{e^{-rU_0} U_0^{\sum_{i=1}^{r} x_i}}$$

$$= \frac{e^{-r\left(\frac{t'}{\theta_1}\right)} \left(\frac{t'}{\theta_1}\right)^n}{e^{-r\left(\frac{t'}{\theta_0}\right)} \left(\frac{t'}{\theta_0}\right)^n} \qquad \left(\text{Since } n = \sum_{i=1}^{r} x_i\right)$$

$$= \frac{e^{-\left(\frac{rt'}{\theta_1}\right)} \left(\frac{rt'}{\theta_1}\right)^n \Big/ n!}{e^{-\left(\frac{rt'}{\theta_0}\right)} \left(\frac{rt'}{\theta_0}\right)^n \Big/ n!}$$

$$= \frac{e^{-\left(\frac{t}{\theta_1}\right)} \left(\frac{t}{\theta_1}\right)^n \Big/ n!}{e^{-\left(\frac{t}{\theta_0}\right)} \left(\frac{t}{\theta_0}\right)^n \Big/ n!} \qquad (\text{Since } t = rt')$$

$$= \frac{P\{N_t = n \mid \theta = \theta_1\}}{P\{N_t = n \mid \theta = \theta_0\}}$$

which completes the proof.

DERIVATION OF PROBABILITY RATIO SEQUENTIAL TEST (PRST)

1. Definition of Likelihood Function:

First, assume that

$$P(X;\theta;t) = \frac{e^{-\frac{t}{\theta}}\left(\frac{t}{\theta}\right)^{x}}{x!} = \left\{\begin{array}{l}\text{The probability of exactly}\\ \text{x failures occurring when}\\ \text{t and } \theta \text{ are unknown}\end{array}\right\}$$

Now, assume that successive observational values on x_i ($i = 1, 2, \ldots, n$) are obtained for n independent trials where each trial is a fixed time interval of length t'. (That is, x_1 failures occur in the first time interval of length t', x_2 failures occur in the second time interval of length t', etc.) Then the likelihood function, L, defined by

$$L(x_1, x_2, \ldots, x_n;\theta;t') = P(x_1;\theta;t')\cdot P(x_2;\theta;t')\cdots P(x_n;\theta;t')$$

yields the probability that the sample $(x_1, x_2, \ldots x_n)$ would occur in exactly that order, if the true MTBF, θ, is known. Letting $U = \frac{t'}{\theta}$ and using the Poisson probability function (above), the following formula is derived for the likelihood function:

$$L(x_1, x_2, \ldots, x_r;\theta;t') = \frac{e^{-U}\,U^{x_1}}{x_1!} \cdot \frac{e^{-U}\,U^{x_2}}{x_2!} \cdots \frac{e^{-U}\,U^{x_r}}{x_r!}$$

$$= \frac{e^{-rU}\,U^{\sum_{i=1}^{r} x_i}}{\prod_{i=1}^{r} x_i!}$$

2. Probability Ratio Theorem:

Consider the ratio

$$R = \frac{L(x_1, x_2, \ldots, x_r;\theta_1;t')}{L(x_1, x_2, \ldots, x_r;\theta_0;t')}$$

which is the ratio of the probability of obtaining the observed sample assuming θ_1 is true to the probability of obtaining that same sample assuming θ_0 is true. Now letting $t = rt'$, and $x_1 + x_2 + \ldots + x_r = n$, it will be proved that

$$R = \frac{P\{N_t = n \mid \theta = \theta_1\}}{P\{N_t = n \mid \theta = \theta_0\}}$$

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3. The PRST Technique:

Since

$$R = \frac{P\{N_t = n \mid \theta = \theta_1\}}{P\{N_t = n \mid \theta = \theta_0\}}$$

if $R > 1$, then the probability of obtaining exactly n failures in time t is greater under the assumption that θ_1 is true than it is under the assumption that θ_0 is true; hence, we tend to believe that $\theta = \theta_1$. Similarly, if this ratio is less than unity we tend to believe that $\theta = \theta_0$. Thus, constants A and B must be found so that one may

(i) Reject if $R \geq A > 1$

(ii) Accept if $R \leq B < 1$

consistent with the prescribed consumer and producer risks α and β. Exact determination of the constants A and B has not been accomplished; however, it has been proven[1] that these risks will not be violated if we use

$$A = \frac{1-\beta}{\alpha}$$

$$B = \frac{\beta}{1-\alpha}$$

with α and β defined by the expressions

$$\alpha = P\{N_t \geq n_1 \mid \theta \geq \theta_0\} = \text{producer risk}$$

$$\beta = P\{N_t \leq n_2 \mid \theta \leq \theta_1\} = \text{consumer risk}$$

where n_1 corresponds to the value of n under condition (i) above and n_2 is the value of n when condition (ii) takes place. (NOTE: In these expressions, θ_0 and θ_1 are assumed fixed and known, whereas θ is assumed fixed but unknown.)

Thus, the following accept/reject criteria may be established:

(a) Reject if $R \geq \frac{1-\beta}{\alpha}$

(b) Accept if $R \leq \frac{\beta}{1-\alpha}$

[1] See Wald's "Sequential Analysis" published by John Wiley & Sons, Inc., Chapman and Hall Ltd., London (1947)

and take an additional observation if

$$\frac{\beta}{1-\alpha} < R < \frac{1-\beta}{\alpha}$$

The particular decision points may be found in advance by expressing test time as a function of α, β, θ_o, θ_1, and n. This is accomplished as follows. Under condition (a) above

$$R = \frac{P\{N_t = n \mid \theta = \theta_1\}}{P\{N_t = n \mid \theta = \theta_o\}} \geq \frac{1-\beta}{\alpha}$$

But letting $d = \theta_o/\theta_1$

$$\frac{P\{N_t = n \mid \theta = \theta_1\}}{P\{N_t = n \mid \theta = \theta_o\}} = \frac{e^{-t/\theta_1}\left(\frac{t}{\theta_1}\right)^n \Big/ n!}{e^{-t/\theta_1}\left(\frac{t}{\theta_o}\right)^n \Big/ n!}$$

$$= d^n e^{t\left(\frac{1-d}{\theta_o}\right)}$$

Thus,

$$d^n a^{t\left(\frac{1-d}{\theta_o}\right)} \geq \frac{1-\beta}{\alpha}$$

Hence,

$$n \ln d + t\left(\frac{1-d}{\theta_o}\right) \geq \ln\left(\frac{1-\beta}{\alpha}\right)$$

and finally

$$(A_1): \; t_n \leq \theta_o \left[\frac{\ln\left(\frac{1-\beta}{\alpha}\right) - n(\ln d)}{1-d}\right]$$

Similarly, under condition (b) above

$$(A_2): \; t_n \geq \theta_o \left[\frac{\ln\left(\frac{\beta}{1-\alpha}\right) - n(\ln d)}{1-d}\right]$$

that is, (A_1) gives maximum test time for rejectance if n or more failures have occurred in time t_n, and (A_2) gives minimum test times for acceptance if n or less failures have occured in time t_n.

TRUNCATION OF POISSON SEQUENTIAL TEST (PST)

It was noted in Chapter 3 of this document that the PST procedure (unlike the PRST) will not continue indefinitely. Eventually a point shall be reached where the number of failures permitted for acceptance is one less than the number of failures specified for rejection for the same amount of operating time, at which point the test will necessarily end. However, the test may be truncated much earlier as a result of the following considerations:

The specific decision criteria which is derived from the use of the PST procedure takes the following form:

Col 1 Test Time	Col 2 Accept if Quantity of Failures (X) Equal or Less Than:	Col 3 Reject if Quantity of Failures (X) Equal or Greater Than	Col 4 Continue if Quantity of Failures (X) Satisfies
T_1	X_1		$X_1 < X < X_2$
T_2		X_2	$X_1 < X < X_2$
T_3	X_3		$X_3 < X < X_4$
T_4		X_4	$X_3 < X < X_4$
T_5	X_5		$X_5 < X < X_6$
T_6		X_6	$X_5 < X < X_6$
etc.	etc.	etc.	etc.

NOTE: Although it is not necessarily true that acceptance/rejection points will alternate with successive T_k's, as they do in the above table, whether or not this alternation occurs has no bearing on what follows. The alternation merely makes the truncation procedure easier to follow.

A condition may now be specified for terminating this test at T_5 (or any other T_k for $k \geq 3$; or, more generally, at any reject point past the first one). First, it is obvious that a condition for termination would not be necessary unless for each k ($k = 1, 2, \ldots 5$), at test time T_k, the conditions of Col 4 were true. If N_T denotes the number of failures in time T, and if we are in the continue test region at time T_5, then the following events must have taken place:

$$A_1 = \left\{X_1 < N_{T_1} < X_2\right\}$$

$$A_2 = \left\{X_1 < N_{T_1} + N_{T_2 - T_1} < X_2\right\}$$

$$A_3 = \left\{X_3 < N_{T_2} + N_{T_3 - T_2} < X_4\right\}$$

$$A_4 = \left\{X_3 < N_{T_3} + N_{T_4 - T_3} < X_4\right\}$$

$$A_5 = \left\{X_5 < N_{T_4} + N_{T_5 - T_4} < X_6\right\}$$

Now N_{T_1} can only take on a finite number of integral values between X_1 and X_2. Let them be $a_1, a_2, \ldots, a_{n_1}$. Choose a_1 (first) and write

$$A_1 = \left\{N_{T_1} = a_1\right\}$$

Once a_1 is specified, $N_{(T_2 - T_1)}$ can only take on a finite number of integral values in order to satisfy the condition $\left\{X_1 < a_1 + N_{T_2 - T_1} < X_2\right\}$. Let them be $a_{11}, a_{12}, \ldots, a_{1n_2}$. Choose a_{11} (first) and write the event

$$A_{11} = \left\{N_{T_2 - T_1} = a_{11}\right\}$$

Continue in this manner, that is, assume a_1 failures occurred in time T_1 and a_{11} failures occurred in time $T_2 - T_1$, then $a_{111}, a_{112}, \ldots, a_{11n_3}$ are the only possibilities for the numbers of failures occurring in time $T_3 - T_2$ in order to satisfy the inequality $\left\{X_3 < a_1 + a_{11} + N_{T_3 - T_2} < X_4\right\}$ so that one may first choose the event

$$A_{111} = N_{T_3 - T_2} = a_{111}$$

Eventually we derive <u>one particular way</u> that an equipment can stay in the continue test region up to time T_5, namely, by each of the following events occurring in successive time intervals:

$A_I = \{N_{T_1} = a_I\}$

$A_{II} = \{N_{(T_2 - T_1)} = a_{II}\}$

$A_{III} = \{N_{(T_3 - T_2)} = a_{III}\}$

$A_{IV} = \{N_{(T_4 - T_3)} = a_{IV}\}$

$A_V = \{N_{(T_5 - T_4)} = a_V\}$

Now, it is well known that for the exponential distribution successive time intervals are independent, that is, the probability of failure in one interval is not affectad by the number of failures that occurred in a previous time interval. Thus, we may writa

$$P_1 = P\{A_I \text{ and } A_{II} \text{ and } A_{III} \text{ and } A_{IV} \text{ and } A_V\}$$
$$= P\{A_I\} \cdot P\{A_{II}\} \cdot P\{A_{III}\} \cdot P\{A_{IV}\} \cdot P\{A_V\}$$
$$= \prod_{i=1}^{V} P\{A_i\}$$

If A_i is changed to $\{A_i \mid \theta = \theta_1\}$ then P_1 will give the probability that equipment as bad as θ_1 would have stayed in the continue test region through time T_5 in exactly the manner specified by the A_i's. Then by summing all possible P_i's that can be derived in this way, one can compute the probability that equipment as bad as θ_1 would have remained in the continue test region. Thus, one may terminate the test at time T_k where this final probability is less than or equal to β (the predetermined risk that unsatisfactory equipment will be accepted).

Because of the cumbersome notation required to give a theoretical explanation of this truncation procedure, only one of the many possible

ways of reaching T_5 (without causing an accept/reject decision) was given. Another, way, of course, is to chooee a_1 at the firet step, then choose a_{12} at the second etep (instead of a_{11}). Ultimately, this leade to:

$A_1 = \{N_{T_1} = a_1\}$

$A_{12} = \{N_{(T_2 - T_1)} = a_{12}\}$

$A_{121} = \{N_{(T_3 - T_2)} = a_{121}\}$

$A_{1211} = \{N_{(T_4 - T_3)} = a_{1211}\}$

$A_{12111} = \{N_{(T_5 - T_4)} = a_{12111}\}$

In fact, one may derive all the poseible waye that thie may happen, where all avants are expreseed in terms of the successive tima intervals between decision points. A concrete example will serve to convince those in doubt:

Test Time	Accept if Quantity of Failures less Than or Equal to:	Reject if Quantity of Failuree Greater Than or Equal to:	Continue if Quantity of Failures Equal to:
T_1=160	0	--	1 or 2
T_2=195	--	3	1 or 2
T_3=[illegible]	[illegible]	4	1, 2, or 3
T_4=300	1	--	2, 3, or 4
T_5=385	--	5	2, 3, or 4
T_6=430	2	--	3, 4, or 5
T_7=485	--	6	3, 4, or 5
etc.	etc.	etc.	etc.

The above table was derived by using the PST decision rule using 20% risk conditions. Let us attempt to truncate the test (by the procedure explained above) at test time T_3 = 285 hours, assuming that θ_1 = 100 hours. The main problem is to list all possible ways of staying in the continue test region up to and including time T_3. The following schematic diagram shows how simple this is:

<table>
<tr><td></td><td colspan="3">QUANTITY OF FAILURES THAT MAY OCCUR</td></tr>
<tr><td>In Time
T_1 - 0 = 160</td><td colspan="2">1   or</td><td>2</td></tr>
<tr><td>In Time
T_2-T_1 = 35</td><td colspan="2">If 1 at time T_1 then
0   or   1</td><td>If 2 at time T_1 then
0</td></tr>
<tr><td>In Time
T_3-T_2 = 90</td><td>If 1+0(= 1) at time T_2 then
0, 1, or 2</td><td>If 1+1(=2) at time T_2 then
0 or 1</td><td>If 2 + 0(=2) at time T_2 then
0   or   1</td></tr>
</table>

Thus, there are 7 possible ways of remaining in the continue test region through test time T_3:

	QUANTITY OF FAILURES THAT MAY OCCUR						
In Time T_1 - 0 = 160	1	1	1	1	1	2	2
In Time T_2 - T_1 = 35	0	0	0	1	1	0	0
In Time T_3 - T_2 = 90	0	1	2	0	1	0	1

The question now to be answered is: What is the probability that equipment as bad as θ_1 = 100 hours MTBF would behave in any of these seven ways? This is answered by computing each of the seven column probabilities, and

then summing the seven results. Giving the details for Column 1 only we get:

Col 1: $P\left\{N_{160} = 1 \text{ and } N_{35} = 0 \text{ and } N_{90} = 0\right\}$

$$= P\left\{N_{160} = 1\right\} \cdot P\left\{N_{35} = 0\right\} \cdot P\left\{N_{90} = 0\right\}$$

$$= \frac{e^{-\frac{160}{100}}\left(\frac{160}{100}\right)^1}{1!} \cdot \frac{e^{-\frac{35}{100}}\left(\frac{35}{100}\right)^0}{0!} \cdot \frac{e^{-\frac{90}{100}}\left(\frac{90}{100}\right)^0}{0!}$$

$$= (.32)\ (.71)\ (.41)$$

$$= .093$$

Similarly,

Col 2: .083

Col 3: .038

Col 4: .032

Col 5: .030

Col 6: .076

Col 7: .068

The sum of these probabilities is .42 = 42%. Since the final result exceeds the original risk condition (20%) it is concluded that it is not possible to truncate the test without contradicting the prescribed risk. (It can be shown, however, that truncating at 3.85 gives a result which is compatible with 20% risks.)

DEFINITIONS

1. RELIABILITY. The probability of failure-free operation in a given amount of operating time. (NOTE: This is a "mathematical", not an "engineering" definition. The "engineering" definition would add such phrases as "when operated under specified conditions", or "when used in the intended environment".)

2. MTBF (Mean-Time-Between-Failure). The arithmetic average of all failure-free operating intervals during the "useful life" of the equipment. As used herein, MTBF has meaning only if the failure behavior can be described by the exponential or Poisson distributions.

3. USEFUL LIFE. The period (between the end of the burn-in stage and the beginning of the wear-out stage) during which a constant failure rate is exhibited.

4. FAILURE RATE. The reciprocal of MTBF.

5. CONSUMER'S RISK. The probability that unsatisfactory equipment will be accepted.

6. PRODUCER'S RISK. The probability that satisfactory equipment will be rejected.

7. MTBF UPPER BOUND. A value of MTBF which represents the required value or objective. Values of MTBF greater than or equal to the MTBF upper bound are considered satisfactory.

8. MTBF LOWER BOUND. A value of MTBF which represents an unacceptable value. Values of MTBF less than or equal to the MTBF lower bound are considered unsatisfactory.

9. ZONE OF INDIFFERENCE. Values of MTBF (greater than the MTBF lower bound and less than the MTBF upper bound) which are considered neither satisfactory nor unsatisfactory. The probability of accepting (rejecting) such equipments is permitted to rise higher than the predetermined consumer (producer) risk level.

10. DISCRIMINATION RATIO. The ratio of "MTBF upper bound" to "MTBF lower bound".

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SYNTAX

α : Producer's risk.

β : Consumer's risk.

θ : True MTBF

θ_o: MTBF Upper Bound

θ_1: MTBF Lower Bound

θ^*: MTBF Requirement (when upper and lower bound values have not been chosen).

d : Discrimination Ratio (θ_o/θ_1).

N_t: The number of failures that occur in time t.

$P(x;\theta;t)$: The probability that N_t is equal to x, if θ is known.

$C(x;\theta;t)$: The probability that N_t is less than or equal to x, if θ is known.

$D(x;\theta;t)$: The probability that N_t is greater than or equal to x, if θ is known.

PFTT: Poisson Fixed Time Test.

PST: Poisson Sequential Test.

PRST: Probability Ratio Sequential Test.

$P\{A|B\}$: The probability that A occurs given that B is true. Usually, B is a statement such as "$\theta \leq \theta^*$", where θ^* is a fixed, known value and θ is a fixed unknown value.

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SECTION VI

VERIFICATION OF QUANTITATIVE RELIABILITY REQUIREMENTS - DECISION CRITERIA

SECTION VI

VERIFICATION OF QUANTITATIVE RELIABILITY REQUIREMENTS - DECISION CRITERIA

FOREWORD

This section presents guidance to Electronic Systems Division (ESD) SPOs in the statistical aspects of planning equipment reliability demonstrations.

For one-of-kind equipments with "high" mean-time-between-failures (MTBF) requirements, the present Table I of MIL-R-26474 leads to lengthy test times before a decision can be made on equipment reliability. This section offers methodology for devising alternate approaches to reliability demonstration. In addition, a quantification of the risks involved in equipment reliability decision-making is presented.

As additional thinking is developed on equipment reliability demonstration, it is planned to revise this document.

SECTION VI

CONTENTS

FIGURE		PAGE

ATTACHMENTS

Chapter 1

INTRODUCTION

This section gives a straightforward explanation of the mathematical tools that are available for demonstrating the reliability of electronic systems/equipment through testing. Most presentations of these techniques fail to set forth the underlying ideas and neglect to exemplify their logical coherence. It is for this reason that confusion prevails as to the meaning and value of a statistical assessment of Mean Time Between Failure (MTBF) and other Reliability indices. The purpose of this section is to show that these tools are not mere compilations of arbitrary rules to be learned by rote; nor are they techniques to be acquired by imitation and used without consideration of the equipments involved; but rather they must be developed logically from a few fundamental principles in accordance with the:

(1) Number of models available for testing;

(2) Contractual MTBF requirement; and

(3) Determination of risk levels that are consistent with schedules, cost of testing, test environment, and equipment characteristics.

Relatively few tools are needed to accomplish this task, and they are amazingly simple to apply in the special case of electronic equipments. It is only when these techniques are stated generally (so that they apply to quality control, biological studies, insurance considerations, etc.) that they take a complicated form.

These introductory remarks should make it clear that this section stresses the fact that no military specification can provide optimum criteria upon which to assess the reliability of electronic systems. Yet, many programs have been using MIL-R-26474 in exactly this way. Table I of MIL-R-26474 has been cited in many equipment specifications despite its unreasonableness when the number of models available for test is small and the MTBF requirement is high. For example, if the MTBF requirement is 1,000 hours, Table I requires 3,000-10,000 hours of testing, and only when the equipment is extremely better or extremely worse than the contractual requirement will an accept/reject decision be made at the 3,000 hour point. If the true MTBF lies in the 500-1,000 hour range, it is quite likely that 6,000 hours of testing or more will be required. If only two models were available for testing, this period of indecision could last six months or more. In fact, it is not unusual to see equipment specifications cite Table I in one paragraph, thereby requiring (possibly) three to six months of indecision, but then, in another paragraph, provide only 75 days (or less) of acceptance testing during which time reliability testing is to be conducted. The result, of course, is that Table I is unenforceable and there is essentially no reliability demonstration criteria in force. Under these conditions, reliability testing is little more than a debugging exercise, and we are forced to accept whatever MTBF is achieved.

Another indication that there is a lack of understanding of Table I is that equipment specifications frequently state "The contractor shall prove to a 90% confidence that the equipment MTBF equals or exceeds (say) 700 hours in accord- with Table I of MIL-R-26474". It is quite unfortunate, but true, that few are aware of the fact that Table I is based on giving confidence that the true MTBF is not lower than one-half the required 700 hours. It is even inadvisable to state "90% confidence that the equipment MTBF exceeds 350 hours", since this implies that our 90% confidence is associated with some figure greater than 350. Actually, the confidence figure reduces considerably as we progress upwards from 350 to numbers close to 700, when Table I criteria is stipulated. It appears that the expression "90% confident that the true MTBF is not lower than 350 hours" is the least misleading, but even this formulation is an interpretation of another mathematical statement[1]. When confronted with these facts, an immediate reaction is to want 90% confidence that 700 hours has been achieved, that is, Table I appears unsatisfactory. Such a change, however, may nullify the original purpose of the demonstration because of the length of test time required before decisions can be made. The higher these figures are set, the longer it will take to accept (reject) equipment which is satisfactory (unsatisfactory)[2]; hence, they must be set in accordance with the consequences of delayed decisions.

Besides providing educational material for those concerned with or affected by reliability programs, this section should serve as a working guide for Reliability Monitors. Although demonstration plans should be tailor-made to the particular system/equipments under procurement, "homemade" plans which lack analysis of the risks involved are to be discouraged. This pamphlet is primarily concerned with the methods available for keeping risks, as well as test time, at minimum levels. This is accomplished via the concept of "Sequential Testing" which was first developed by Wald[3]. Unfortunately, neat formulas were developed for devising sequential tests, causing workers in the field to soon forget the basic concepts upon which the formulas were based. These basic ideas are fully discussed herein - the formulas are only mentioned in order to discuss their limitations. Table I is just one specific instance of these formulas, with "risk factors" and a "discrimination ratio" being arbitrarily fixed in advance. (The quoted terms are explained in Chapter 3) Once this is understood by everyone concerned (and only elementary algebra and analytic geometry are prerequisite for understanding these ideas) realistic demonstration criteria, which is capable of being enforced, may be devised to fit particular programs. It is even conceivable that demonstration criteria may be stipulated and (more often) partially verified during Category I testing, with full verification occurring early in the Category II test program. Usually, formal reliability testing is specified only as a part of final acceptance testing when it is quite late to make significant changes to

[1] The precise statement is explained in Chapter 3, namely, "the probability of accepting equipment with MTBF = 350 is 10% (or less)"

[2] MIL-R-26667A has a plan which uses 2/3 the requirement (Method 2).

[3] "Sequential Analysis" by A. Wald, John Wiley & Sons, Inc., Chapman and Hall Ltd., London (1947).

the reliability of the equipments. If Reliability truly is a function of the design, verification of this design feature must be made as early as possible in the program.

In order to give a better understanding of this presentation, included in Chapter 2 is the basis for using probabilistic theories (namely, the cumulative Poisson distribution) for predicting the reliability of electronic equipments. Also included in Chapter 2 is the establishment of measures of reliability such as MTBF and "failure rate". Those familiar with these ideas may start with Chapter 3 after a brief scanning of Chapter 2.

Some final words of caution before entering upon the main subject matter: Any statistical assessment of Reliability is meaningless unless ground rules have been clearly established for counting "failures" and measuring "operating time". In order to quantify Reliability, it was necessary to leave certain concepts undefined (namely those just quoted), to be defined for the particular equipments under consideration. A common mistake is to assume that these concepts have been previously defined, and that it is sufficient to simply state the numerical reliability requirements. Moreover, definition of these concepts cannot be accomplished by placing such adjectives as Inherent, Achieved, Delivered, or Operational before the word Reliability. These modifiers are useful for conversational purposes but they cannot take the place of unambiguously specifying relevant and non-relevant failure classifications, and precisely defining what is meant by operating time. The methods employed here assume that these ground rules have been precisely defined. It is also mandatory that a failure reporting system has been established to record and analyze failures that occur. This section is concerned with measuring reliability during the constant failure rate zone only; and although it is the contractor's responsibility to thoroughly debug the equipment before MTBF demonstration begins, we cannot close our eyes to the types of failures that occur.

CHAPTER 2

ESTABLISHING A SCIENTIFIC DEFINITION OF RELIABILITY (THE CUMULATIVE POISSON DISTRIBUTION FUNCTION)

2.1 Statement of the Problem. The first attempt to quantify reliability was "the probability that e device will perform its intended function for the period of time required under the opereting conditions encountered". A few moments of quiet thought should be enough to convince anyone that this definition is hardly scientific. The expressions "perform its intended function" end "opereting conditions encountered" prevent us from thinking clearly when ettempting to essign numbers from 0 to 1, es the mathematical theory of probebility requires. Learning e lesson from Euclid, however (who, without caring where or how his points and lines would be used, nevertheless built his system of geometry) we might simply drop the expression "opereting conditions encountered" and proceed undaunted. It might also make the theory more interesting to those who leter epply it, since they would heve the important task of simuleting the expected opereting conditions. But we still heve troubles - the expression "perform its intended function" is vague, meaning different things to different people. We could convert this expression to "not fail" and such e transformation might et first eppear to remove ambiguities; but further examinetion reveels thet the gein is superficial, and so (learning enother lesson from pest scientific progress) we conclude that we are struggling with an indefineble concept. We heve enother one of these elusive creetures in our definition, namely "time", and although we already know how to meesure time, we simply cannot consider all calendar time (for example, repair time). Here egain, we look et Euclid and see that he worried little ebout the definition of e point. Rather, he left it undefined, so thet his theory could epply just es well to e molecule, e pencil point, e spot of gress, or even Pike's Peak. Possibly our theory will epply regardless of how the users of the theory define "failures" and "operating time". Our definition now reads: "The probability thet a device will not feil for the opereting time required", and we are now interested in establishing meesures of reliebility in terms of "operating time" and the number of "feilures" that occur, where the quoted terms are left undefined.

2.2 Establishing Measures of Reliability. Let us essume thet it hes been (unambiguously) specified how to determine that e failure has occurred, and when the equipment is in an opereting state. We could then operate the device until e feilure occurs, correct the feilure, and continue operetion until the next feilure, again take corrective ection, and so on. After e certain period of (opereting) time, we could look back and count the number of failures that occurred, say x. Can x be used es the measure of reliebility? No, since x could be larger or smaller depending on the amount of opereting time t. How ebout using the ratio t/x es our measure, thet is, the total

[1] This is not strictly [illegible], as will be seen [illegible]. See also Chap[illegible] paragraph)

PRECEDING PAGE BLANK

operating time divided by the total number of failures? Intuitively, we would consider this number as the "mean time between failures" (MTBF) that was demonstrated during this operating period. (The reciprocal of this number, which we denote by λ, might reasonably be called the "failure rate", that is, $\lambda = x/t = 1/MTBF$.) But what does this say about the probability of not failing during future periods of operation? Can we use this figure to predict the number of failures that will occur in future operating periods? For example, if a device has five failures in 1,000 hours of operation, we derive the figure 200 hours MTBF. Does this mean that we can expect a failure to occur approximately every 200 hours in the future? One readily sees problems here, and fortunately this problem has been studied for centuries by probability theorists so that a logical approach may be given. The following paragraphs give the basic assumptions contained in this approach.

2.3 The Basis for the Definition. Besides games of chance, certain physical phenomena (such as the occurrences of defectives produced in a manufacturing process, errors in clerical operations, and most important, occurrences of failures in electronic devices during a "certain" period of their life) exhibit a so called statistical regularity which enables us, in spite of their unpredictable nature, to predict their behavior "in the long run".[2] A good example of a mass phenomenon suitable for the application of this theory is the inheritance of certain characteristics; for example, the color of flowers resulting from the fertilization of large numbers of plants of a given species by the pollen of a given plant of the same species. A further example is the whole class of insured men and women whose ages at death have been registered by an insurance firm. Still another is the class of resistors with a certain serial number which is manufactured by a particular firm, whose length of life has been recorded. The properties inherent in all of these examples have been assigned technical terms, such as randomness and stochastic independence, but we have no need of these terms and shall not use them. We simply state here rather crudely that, after a certain "burning-in" period, there is a statistical regularity to the occurrence or non-occurrence of failures in electronic devices, and that this regularity persists until the device reaches old age, that is, the wear-out stage. What makes the situation even nicer is that the burning-in stage is usually fairly short relative to this period of uniform behavior. We may even give an idealized graphical picture of occurrences of failures (known as the "bathtub" curve) as shown in Figure I. This curve illustrates that the failure rate is quite high during the infant stage, then remains constant for a long period of time until reaching the wear-out stage. The existence of this constant zone is what is meant by statistical regularity, and justifies our use of the basic laws of probability theory. A brief listing of these laws (which shall be used sparingly in subsequent paragraphs) is included in Attachment 1.

[2] Briefly, this means that we could, if we were so inclined, continue our experiment to indefinite lengths. For example, in tossing a certain coin, we might see "heads" occurring about half the time. This does not mean that for some finite number of tosses "heads" *must* appear exactly one half the time, but that, as the number of tosses increases (indefinitely) the relative frequency of occurrence of heads gets closer to 1/2.

THE "BATHTUB" CURVE

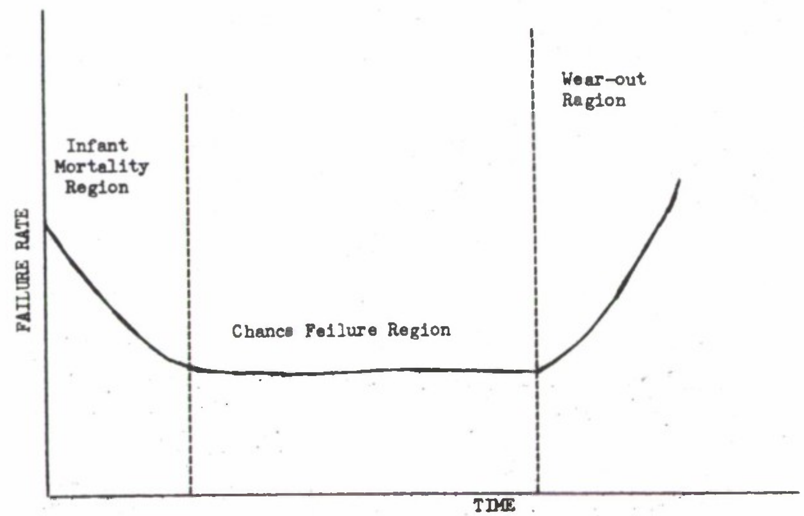

Figure 1

2.4 The Definition. Probability theorists have derived for us what is called the binomial frequency function which applies to experiments which, in addition to satisfying basic laws of probability, are only interested in the occurrence or non-occurrence of an event (a failure, for instance). If we know the probability p of the event occurring in any one trial of the experiment,[3] so that the probability of the event not occurring is (1-p), then the probability of obtaining exactly x occurrences of the event in n trials defines what is known as the binomial (or sometimes the Bernoulli) frequency function. (Also called the binomial distribution.) This function is denoted by b(n;x;p) because it depends on n, x, and p where:

n = the number of trials to be made

x = the total number of occurrences of the event in question

p = the probability of the event occurring in any one trial.

It is mostly a mathematical problem to prove that this frequency function is:

$$b(n;x;p) = \frac{n!}{x!\ (n-x)!} \cdot p^x \cdot (1-p)^{n-x}$$

so that it will not be proven here.[4] To illustrate its use we shall try to calculate the probability of obtaining exactly 7 "two's" in 100 tosses of a die, if it is known that the probability of obtaining a "two" in any one toss is 1/6. We have

$$b(100;7;1/6) = \frac{100!}{7!\ (100-7)!} \cdot (1/6)^7 \cdot (1-1/6)^{100-7}$$

$$= \frac{(100)(99)(98)(97)(96)(95)(94)(5^{93})}{(7)(6)(5)(4)(3)(2)(6^7)(6^{93})}$$

$$= \qquad ?$$

and obviously this is too laborious to calculate - even after some simplification. But do not get discouraged, mathematicians have also discovered an

[3] This may be established *a priori* or by using the observed relative frequency of occurrence. For example, in tossing a die we may be concerned with a "two" appearing or not appearing on successive tosses. We may use p = 1/6 as the *a priori* probability or make 1,000 tosses wherein 300 "two's" appeared, thereby considering the fraction 3/10 as most representative of the probability p. In our case we would use the failure rate λ which is observed during the constant zone.

[4] The proof can be found in any standard text on probability theory.

approximation to the binomial frequency function which works reasonably well when p is small and n is large[5]. This is given by

$$b(n;x;p) \simeq \frac{e^{-np}\ (np)^x}{x!}$$

which is called the Poisson frequency function. (Also called the Poisson distribution) Let's try it:

$$b(100;7;1/6) = \frac{e^{-100/6}\ (100/6)^7}{7!}$$

$$= \frac{e^{-16.67}\ (16.67)^7}{5040}$$

$$= \quad .004 \quad \text{(approximately)}$$

With the use of standard mathematical tables or a slide rule we can make this calculation in a few minutes. But usually we are more interested in knowing the probability of achieving r or less occurrences of a particular event (a failure) and this can be found by finding the probabilities when x = 0,1, 2,...,r and by adding all of these results we derive the probability of obtaining r or less occurrences of the event in question. For example, if r denotes the number of "two's" which appear on our die, the

$$\left\{\text{Probability that } r \leq 7 \text{ in } 100 \text{ tosses}\right\} = \sum_{r=0}^{7} b(100;r;1/6) = .008$$

A function so defined is called a cumulative distribution function[6]. Thus far, it might not have been hard to see the analogy between these considerations and our situation. The event of interest is, of course, a failure, and the observed failure rate is the probability p (assuming that our observations occurred during the constant failure rate zone of the bathtub curve). Our only problem is what is n? For our purposes, we are interested in what will happen

[5] In our case the failure rate λ is usually a small number. We shall speak about "n" later.

[6] Such a function may be defined for any random variable r. (See Attachment 1.) The adjective "cumulative" is often included because certain frequency functions, such as the binomial and Poisson are sometimes called *distribution* functions.

over a period of time (which is a continuous variabla) not what happena in "n" independent observations (a discrete variabla). One solution is to tacitly make tha aasumption that "that which holds in tha discrate case alao holds in the continuous caae" and, unhesitantly, raplace n by t in our formula. For intuitive justification we might raason as follows: the n independant triala could be n intervals of ona minuta aach; that is, failures which occur during any minute would be considered to have occurred at the and of that minute. Also, the failure rate could be expressed in minutes. This has tha effect of changing the continuous variable to a discrate ona, and there seems to be little difference (except, possibly, a philosophical one). We could then proceed to empirically justify our actions by comparing theoretical results to actual results. This having already been done for us, we may, with electronic equipments, replace np by $t\lambda$, that is, replace the "number of trials" by "time" and the "probability of a failure occurring in any one trial" by the "failure rata". This change gives us the cumulative Poisson distribution function which has become famous in raliability analysis:

$$\left\{\begin{matrix}\text{Probability that r or fewer}\\ \text{failurea occur in time t}\end{matrix}\right\} = \sum_{x=0}^{r} \frac{e^{-\lambda t}(\lambda t)^x}{x!}$$

Since $\lambda = 1/\text{MTBF}$, if we let MTBF = θ, we have the equivalent form:

$$\left\{\begin{matrix}\text{Probability that r or fewer}\\ \text{failures occur in time t}\end{matrix}\right\} = \sum_{x=0}^{r} \frac{e^{-t/\theta}(t/\theta)^x}{x!}$$

which is the form used for moat reliability calculations. If one ia interasted in the probability of r = 0 failuraa occurring during the period of time t, this expression reduces to:

$$\left\{\text{Probability that 0 failures occur in time t}\right\} = e^{-\lambda t} = e^{-t/\theta}$$

But this probability is exactly what our (verbal) raliability definition reduced to praviously, that is, "the probability that a device will not fail for the operating time raquired." Denoting this expression by R(t), we hava thus accompliahed our task, namely:

$$R(t) = e^{-t/\theta}$$

A graph of this function appears in Figura 2.

THE RELIABILITY FUNCTION

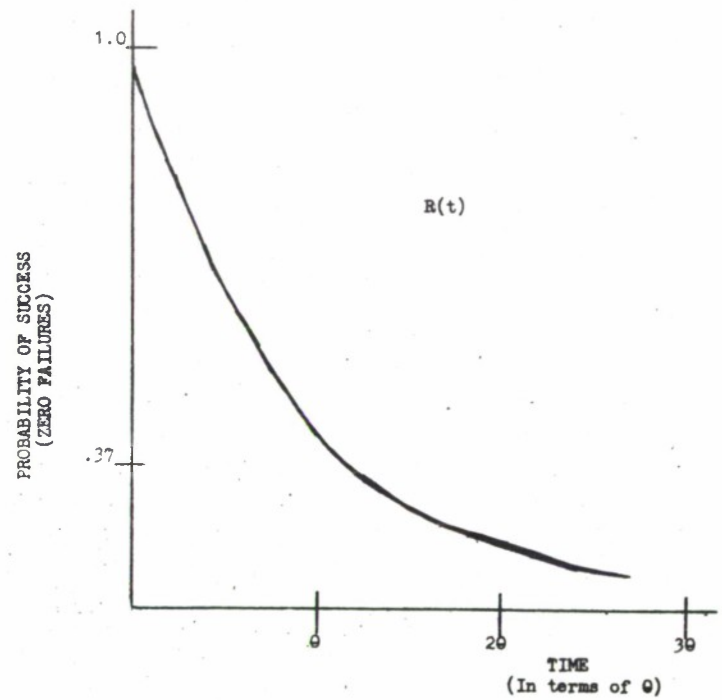

Figure 2

Chapter 3

APPLYING THE CUMULATIVE POISSON DISTRIBUTION TO MTBF DEMONSTRATION

3.1 The Basic Tools. We have thus far developed formulas which have become widely used in reliability analysis. These are the reliability function:

$$R(t) = e^{-t/\theta} \quad = \quad \left\{\begin{array}{l}\text{The probability of zero failures during the} \\ \text{operating time } t\text{, when } \theta = \text{MTBF is known.}\end{array}\right\}$$

Given t and θ, $R(t)$ gives the probability of failure free operation during that time. This function is a special case of the more general cumulative Poisson distribution function which gives the probability of having x or fewer failures in a specified time, if θ is known. For simplicity we denote this probability by $C(x)$, and letting $t/\theta = U$, it takes the form

$$C(x) = \sum_{r=0}^{x} \frac{e^{-U} U^r}{r!} \quad = \quad \left\{\begin{array}{l}\text{The probability of having} \\ x \text{ or fewer failures when} \\ U = t/\theta \text{ is known.}\end{array}\right\}$$

Another formula which can be derived from this one is

$$D(x) = \begin{pmatrix} 1 - C(x-1), \text{ if } x \geq 1 \\ 1, \text{ if } x = 0 \end{pmatrix} \quad = \quad \left\{\begin{array}{l}\text{The probability of having} \\ x \text{ or more failures when} \\ U = t/\theta \text{ is known.}\end{array}\right\}$$

All were derived from the original Poisson distribution function

$$P(x) = \frac{e^{-U} U^x}{x!} \quad = \quad \left\{\begin{array}{l}\text{The probability of having} \\ \underline{\text{exactly}} \ x \text{ failures when} \\ U = t/\theta \text{ is known.}\end{array}\right\}$$

A table of values (rounded off at 3 decimal places) for $P(x)$, $C(x)$, and $D(x)$, for various values of U and x, is given in Attachment 4. All of these formulas were derived from the basic assumption that after a short debugging period, the failure rate of electronic equipments remains constant until reaching the wear-out stage. Now we wish to show how these formulas can be used for the prediction of MTBF through demonstration testing.

3.2 The Technique - The Meaning of Confidence. We mentioned in Chapter 2 an example of a device which (after debugging) exhibited 5 failures in 1,000 hours of operation, and we asked if this demonstrated MTBF of 1,000/5 = 200 hours is meaningful for prediction purposes. When a problem defies solution, one useful technique is to rephrase it. In fact, henceforth, we must develop the ability to rephrase all such questions in terms of the language of our formulas. Let's try this. We might change our question to: What is the probability of a device

having 5 or less failures in 1,000 hours of operation, if its true MTBF is less than 200 hours? This is better, but still not satisfactory since our formulas require that we know how much less. So let's pick a specific number less than 200, say 100 hours. (This number might be called the "absolute minimum MTBF".)[1] Now we're in business - we simply calculate U = 1,000/100 = (test time)/(abs. min. MTBF) = 10, then find U = 10 in the tables (Attachment 4) and then reading across from x = 5 we see that $C(x) = .067 = 7\%$ approximately. That is, a device whose true MTBF is 100 hours has only about a 7% chance of having 5 or less failures in 1,000 hours of operation. We might then say that under this demonstration we are 100%-7% = 93% confident that the true MTBF is not less than 100 hours (which seems to be a fairly high confidence, if the minimum requirement were, in fact, 100 hours). The 7% figure is usually referred to as the Air Force's (or consumer's) risk. The ratio 100/200 = (abs. min. MTBF)/(contractual MTBF) = .5 is called the discrimination ratio. But suppose we had chosen 150 hours instead, giving 150/200 = (abs. min. MTBF)/(contractual MTBF) = .75 as our discrimination ratio? Following the same procedure, with U = 1,000/150 = 6.66 (which must be approximated by 6.5 in order to use our tables) we can be about 63% confident that the true MTBF is not less than 150 hours (which seems not a very high confidence). In fact, the closer we get to 200 hours (that is, the higher our discrimination ratio) the lower U becomes, and the lower our confidence is. On the other hand, if the test time had been longer, say 2,000 hours, and we had experienced 10 failures, we still get the same computed MTBF of 200 hours, but now (using the tables again, first with U = 2,000/100, x = 10; and then with U = 2,000/150, x = 10) we can be 99% confident that the MTBF is not less than 100 hours, and 77% confident that the MTBF is not less than 150 hours. (The reader should verify all of these figures in the tables to be certain of his understanding of the procedure.) Thus, we see that an increase in test time can give a significant increase in confidence.

3.3 The Technique - The Producer's Risk. Let's now look at another question. Suppose operational requirements were such that the device mentioned above had to have an MTBF of 250 hours.[2] Having experienced 5 failures in 1,000 hours of testing should it be rejected? (The computed MTBF is again 200 hours.) Rephrasing again, what is the probability of a device having 5 or more failures in 1,000 hours if its true MTBF is 250 hours? Here U = 1,000/250 = (test time)/(true MTBF) = 4, and reading across from x = 5 we see that $D(x) = 37\%$. We may interpret this as saying that there is a 37% chance that good equipment is being rejected, which seems rather high. (The figure 37% is usually called the producer's risk.)

[1] Task Group 1 of AGREE (Advisory Group on Reliability of Electronic Equipment) reported (June 1957) that there are at least three possible meanings which can be associated with minimum acceptability figures for reliability: (a) that value which the operational commander will tolerate and below which he would take drastic action to initiate improvements, (b) that value which agrees with the current reliability values observed for each class of equipment; and (c) that value which the current state-of-the-art could achieve. We have in mind here that the "absolute minimum MTBF" could be set in accordance with (a) and the "contract MTBF" could be set in accordance with (b) or (c).

[2] This is not the place to discuss the meaning (or consequences) of accept or reject decisions since we are mostly interested in explaining methodology for reaching such decisions. It is expected, however, that we are not talking about accepting or rejecting the particular equipment(s) under test, but rather the design and/or manufacturing process (insofar as reliability is affected).

Again, if the test time was extended to 2,000 hours with 10 failures occurring, U = 2,000/250 = (test time)/(true MTBF?) = 8, and reading across from x = 10 gives D(x) = 28% chance of rejecting good equipment, which is somewhat lower; that is, the producer's risk also lessened as the test time increased.

3.4 A Technique to Keep "Risks" and "Test Time" Low. These two risks (consumer's, producer's) are present in any accept/reject criteria which is based on the number of failures which occur during a specified test time. The tables in Figure 3 give a listing of these risks for various periods of test time and varying numbers of allowable failures. In these tables it is assumed that the contractual MTBF is 200 hours, and "allowable failures" means that we accept if the number of failures is less than or equal to that number, and reject otherwise. The AF risk indicated is based on a .5 discrimination ratio, that is, we have assumed that the absolute minimum MTBF requirement is 100 hours. Remember, in this context, A% confidence means that there is a 1-(A%) risk that equipment having MTBF = 100 hours will pass the test. In other words, we should not speak of the confidence figure without also stating the discrimination ratio that is being used. Now let's look at these tables to see if we can determine an optimum test duration and an optimum number of allowable failures for demonstrating reliability. (See Figure 3) As can be seen from these tables, it is extremely difficult to hold both the producer's risk and the AF risk at low levels when a specific test time is set before hand. A quick scanning of these tables shows that if risks of 10% are required by both parties, about 2,000 hours of test time would be necessary (see table (6) with 14 failures allowed). If only one model is available for testing, this means about 3 months of testing even if testing is conducted 24 hours a day (which is usually impossible). However, there are ways of reducing the test time considerably, thereby giving significant savings in time and money. Suppose the test time was set at 2,000 hours, with 14 failures allowed, but after 800 hours of testing only 4 failures had occurred. A glance at table (3) shows that the AF could accept at this point with only 9% risk. The producer's risk at this point is 37% but this figure is irrelevant since we are not rejecting at this point. On the other hand, suppose that after 600 hours 5 failures had occurred. The AF could reject at this point since table (2) shows that the producer's risk is 8%. Again, take note that the corresponding AF risk is 44% but this figure is irrelevant since 5 failures in 600 hours is not being specified for acceptance purposes. To sum up these remarks, it would be nice if these earlier acceptance/rejectance points were built into the demonstration plan. Even using the limited information contained in these six tables, we could construct an acceptance/rejectance plan as follows:

ALLOWABLE FAILURES VS. RISKS FOR PRESELECTED TEST TIMES

(1) TEST TIME: 400 hours

ALLOWABLE FAILURES	PRODUCER'S RISK*	AIR FORCE'S RISK**
0	86%	2%
1	59%	9%
2	32%	24%
3	14%	43%
4	5%	63%

(4) TEST TIME: 1,000 hours

ALLOWABLE FAILURES	PRODUCER'S RISK*	AIR FORCE'S RISK**
3	73%	1%
4	55%	2%
5	38%	6%
6	24%	13%
7	13%	22%
8	6%	33%

(2) TEST TIME: 600 hours

ALLOWABLE FAILURES	PRODUCER'S RISK*	AIR FORCE'S RISK**
0	95%	.2%
1	80%	2%
2	57%	6%
3	35%	15%
4	18%	28%
5	8%	44%

(5) TEST TIME: 1,500 hours

ALLOWABLE FAILURES	PRODUCER'S RISK*	AIR FORCE'S RISK**
5	76%	.2%
6	62%	.7%
7	48%	2%
8	34%	4%
9	22%	7%
10	14%	12%
11	8%	18%

(3) TEST TIME: 800 hours

ALLOWABLE FAILURES	PRODUCER'S RISK*	AIR FORCE'S RISK**
0	98%	.03%
1	90%	.3%
2	76%	1%
3	56%	4%
4	37%	9%
5	21%	19%
6	11%	31%
7	5%	45%

(6) TEST TIME: 2,000 hours

ALLOWABLE FAILURES	PRODUCER'S RISK*	AIR FORCE'S RISK**
7	78%	.07%
8	67%	.2%
9	54%	.4%
10	42%	1%
11	30%	2%
12	21%	4%
13	14%	7%
14	8%	10%

*Producer's risk: The probability that equipment which exactly satisfies the requirement (200 hours) will fail the test.

**Air Force's risk: The probability that equipment which has MTBF equal to 1/2 the requirement (100 hours) will pass the test.

Figure 3

TEST TIME	REJECT IF NUMBER OF FAILURES IS GREATER THAN OR EQUAL TO:	PRODUCER'S RISK	CONTINUE IF NUMBER OF FAILURES IS IN RANGE BELOW	ACCEPT IF NUMBER OF FAILURES IS LESS THAN OR EQUAL TO:	AF RISK
400	5	5%	2-4	1	9%
600	6	8%	3-5	2	6%
800	8	5%	5-7	4	9%
1000	9	6%	6-8	5	6%
1500	11	8%	10	9	7%
2000	15	8%	-	14	10%

If tables had been constructed for 500, 700, 900, 1100-1400, and 1600-1900 hours, even more acceptance/rejectance points could be incorporated which gives greater possibility of a decision being reached prior to 2,000 hours.

CHAPTER 4

SEQUENTIAL TESTING AND MIL-R-26474

The ideas presented in the preceding section come under the name "sequential testing" and have been studied for some time so that formulas are available to select "certain" decision points beforehand. (See Attachment 1.) These formulas are the basis for the test plan given in Table I of MIL-R-26474 and use 10% risk conditions (maximum) and a .5 discrimination ratio.[1] The formulas enable us to state test time more generally - in terms of multiples of contractual MTBF. There is, however, one major problem. Stated simply, the problem is that the formulas do not find the earliest decision points (with 10% risks) but instead find earlier decision points (with risks considerably lower than 10%). The reason for this is a mathematical issue and need not concern us here. However, these formulas are given in Attachment 2 wherein a derivation of Table I is given. Table I appears in Figure 4 (page 19) showing the earlier decision points and the associated risks. Making a comparison between Table I and the table derived in the preceding section shows a marked difference. (Simply divide the test times by 200 to make this comparison.) Ensuing paragraphs will concentrate on the effects of Table I rather than the causes.

The important thing to notice about Table I is that the Producer's Risk and AF Risk stay at about 2% and 3% respectively.[2] This makes the test quite severe (at least more severe than the stated risk levels of 10% indicate) and only equipment which is extremely good or extremely bad is likely to cause a decision early in the test span. Since the main object of sequential testing is to permit decisions to be reached early in the test at predetermined risk levels, it is rather puzzling that the earlier decision points have such low risk levels. In other words, Table I does not accomplish what it apparently set out to do - namely, to permit decisions to be reached early at risk levels of 10%. It may permit early decisions, but it does so at risk levels of 2-3%, that is, 95% confidence for the AF and 2% risk for the producer. Recalling that the confidence should not be stated without also giving the discrimination ratio, we should state it thus: Table I in actuality gives 97% confidence with

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[1]Table I was developed by Task Group 2 of AGREE. Their report was issued by the Office of the Assistant Secretary of Defense (Research and Engineering), 4 Jun 1957.

[2]The Producer's Risk is found by setting U = multiples of contract MTBF and finding D(x) for x = the REJECT figure. The AF Risk is found by setting U = 2 times the multiples of contract MTBF and finding C(x) for x = the ACCEPT figure. To see this, let T denote the time units in Column I, then since the discrimination ratio is 1/2, $U = \left(\frac{\text{test time}}{\text{True MTBF}}\right) = \left(\frac{\text{test time}}{1/2 \text{ contract MTBF}}\right) = 2\left(\frac{\text{test time}}{\text{contract MTBF}}\right) = 2T.$

a discrimination ratio of .5, that is, 97% confidence that the true MTBF is not less than 1/2 of the contractual requirement.

Now let us look at tha effects of using the ebove mentioned formulas for sequential testing, but changing the risk levels end discrimination ratio as follows:

Risk levels: 20% (maximum)
Discriminetion Ratio: .5

Attachment 2 gives the derivetion of the table which is obtained using these values (Table A, see Figure 5). Looking at Table A, we sea that although the risk levels were set at 20% (maximum), they ectually naver reech this level. In fact, the risks stey at 5-8%, except at the very end, when they rapidly rise to 11% for producer and 12½% for the Air Forca.[3] Bear in mind, however, that if sequential testing eccomplishes what its craetors claim, tha 11% and 12½% levels should rerely be reached. In tha cese of Tabla A, this seems quite reesonable since the CONTINUE TEST region is ralatively narrow (ee compared to Table I). A graphicel picture of both Table I and Table A which shows the ACCEPT, REJECT, and CONTINUE TEST regions is given in Figure 6, and illustrates their markad differences. Teble A also ellows less time to reach the first decision point (1.38 multiples of contract MTBF instead of 3) and less maximum test time (8 multiples of contract MTBF instead of 10.3). Essentielly, than, Table A is still giving the Air Force about 90% confidence (with e .5 discrimination ratio) at e considerable sevings in tast time (if the MTBF requirament is high). Whether Table A should be used in preference to Teble I is a question that cen only be answered in consideration of several factors such as:

(1) Number of models available for testing;

(2) Contrectual MTBF raquirament; and

(3) Determination of risk levels that ara consistant with schedulas, cost of testing, test environment, end aquipmant characteristics (for axampla, the amount of davelopment involved).

In the casa of high MTBF requiremants, thera era other considerations which may serve to justify the increased risk levals of Tabla A. Looking first at the increased risks to tha producer, considar that sinca tha Air Force hes backed away from the contrectual MTBF requiremant in order to compute AF Risk, it would not seem unreesonable to expect the producar to compute his risk based on some highar valua than tha contractual MTBF requirament. Certainly, the producer cennot design the equipment MTBF to exact numerical values. One would expect thet efforts would be directed towerd designing somewhat better than the requirement. If we arbitrarily selected "1/4 higher" wa may usa the Poisson tebles to show that the producer's risk is quite low. These risks are indicated in Table A. It is quita aasy to justify the incraasas in AF Risk (especially whan the cost of testing is $1,000 a day or mora) sinca, in the case of high MTBF requiremants, there is a considerable raduction in test

[3] The point for ending the test was arbitrarily selected (by the technique given in Chapter 3).

TABLE I (MIL-R-26474)

ACCEPT-REJECT CRITERIA FOR FAILURE RATE TESTING

Column I Multiples of Contract MTBF	REJECT if number of failures below occur on or before time in Column I	Producer's Risk	CONTINUE test if number of failures fall in range below at time in Col. I	ACCEPT if no more than number of failures below occur by time in Col. I	AF Risk
3.00	8	1%	2-7	1	2%
3.32	8	2%	2-7		
3.58			3-8	2	3%
4.01	9	2%	3-8		
4.27			4-9	3	3%
4.70	10	2%	4-9		
4.96			5-10	4	3%
5.39	11	2%	5-10		
5.65			6-11	5	3%
6.08	12	2%	6-11		
6.34			7-12	6	3%
6.77	13	2%	7-12		
7.03			8-13	7	3%
7.46	14	2%	8-13		
7.72			9-14	8	3%
8.15	15	2%	9-14		
8.41	15	2.5%	10-14	9	3%
9.10	15	4.5%	11-14	10	3%
9.79	15	8%	12-14	11	3%
10.30	15	10%	-	14	9%

Producer's Risk: The probability that equipment which exactly satisfies the contractual MTBF requirement will be rejected at the decision point indicated.

AF Risk: The probability that equipment which only satifies one half the contractual MTBF requirement will be accepted at the decision point indicated.

Figure 4

hours required. (The next chapter is aimed at making this last statement more precise.) But more than test expenditures may be effected - as time passes, it becomes increasingly harder to correct design weaknesses, and increasingly more costly to the producer. In the final analysis, the Air Force bears the burden of both design deficiencies, and increased costs to the producer, whichever may occur as a result of delayed decisions.

Maximum test time may be shortened even further, but only at the expense of increased risks to the producer and consumer. Once a discrimination ratio and "maximim risks" are selected, it is a simple matter to scan the Poisson tables to select a point for ending the test (called a "truncation" point). This technique was explained in Chapter 3, where a truncation point of 2,000 hours (10 multiples of MTBF) was selected. However, when "sequential test formulas" are used, there are formulas which give the first point at which the producer's risk is equal to the "predetermined" level (20% in the case of Table A) and, at the same time, the consumer's risk is <u>less than or equal to</u> the predetermined level[4]. If these formulas had been applied to Table A, the result would have been as follows (with the new risks as indicated):

1.38	4		1-3		0
2.07	5		2-4		1
2.76	6		3-5		2
3.45	7		4-6		3
4.14	7	12½%	5-6		4
4.73	7	20%	-	17%	6

Note that the producer's risk climbs to 20%, while the AF risk never exceeds 17%. If the producer's risk is computed on the basis of designing ¼ higher than the requirement, the last two decision points (4.14 and 4.73 time units) would have risks of 5% and 9% instead of 12½% and 20%. Under certain conditions this plan may be quite reasonable for both parties.

[4] "Truncated life Tests in the Exponential Case," by B. Epstein, Annals of Mathematical Statistics, vol. 25, pages 555-564.

TABLE A

ACCEPT-REJECT CRITERIA FOR FAILURE RATE TESTING

<u>Column I</u> Multiples of Contract MTBF	REJECT if number of failures below occur on or before time in Col. I			CONTINUE test if number of failures fall in range below at time in Col. I	ACCEPT if no more than number of failures below occur by time in Col I.	
1.38	4	5%*	2½%***	1-3	0	6%**
2.07	5	5%	2½%	2-4	1	8%
2.76	6	6%	2½%	3-5	2	8%
3.45	7	6%	2%	4-6	3	8%
4.14	8	6%	2%	5-7	4	9%
4.83	9	6%	2%	6-8	5	9%
5.52	10	6%	1½%	7-9	6	8%
6.21	11	5%	1%	8-9	7	8%
6.90	12	5%	1%	9-11	8	7%
7.59	12	8%	2%	10-11	9	7%
8.00	12	11%	3%	-	11	12½%

*Producer's Risk: The probability that equipment which <u>exactly</u> satisfies the contractual MTBF requirement will be rejected.

**Air Force's Risk: The probability that equipment which satisfies 1/2 the contractual MTBF requirement will be accepted.

***Producer's Risk: The probability that equipment which is 1/4 higher than the contractual MTBF requirement will be rejected. (Note: This is found by setting U = 4/5 times multiples of contract MTBF and finding D(x) for x = the REJECT figure.)

Figure 5

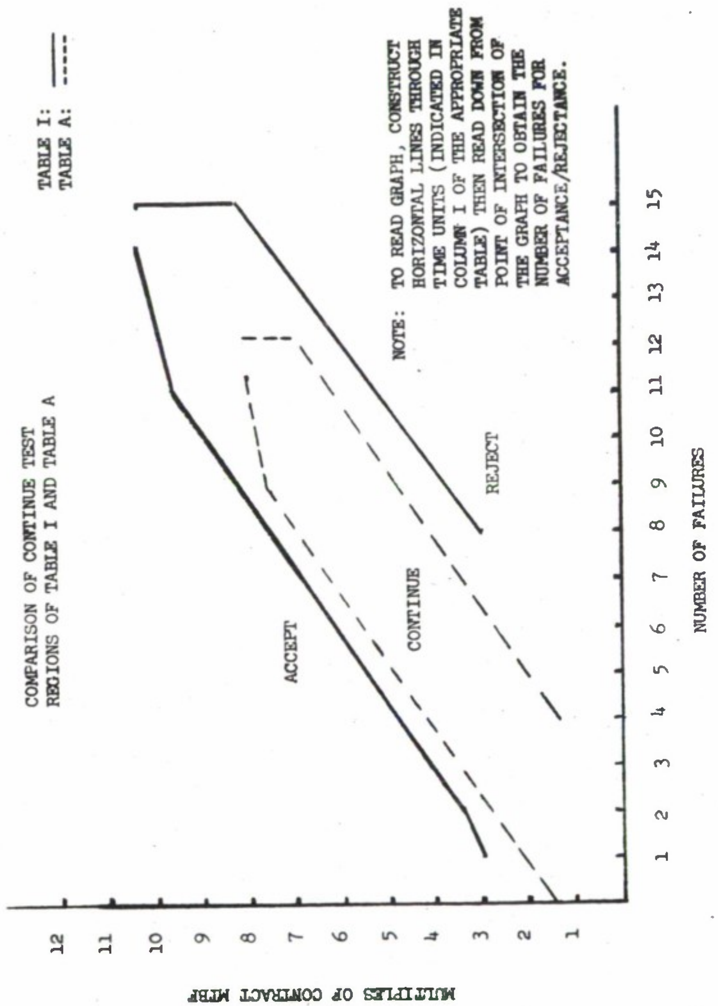

Figure 6

CHAPTER 5

AVERAGE TEST TIME

When the sequential test formulas (as given in Attachment 2) are used, there are still other formulas (see Attachment 3) which give the most probable number of failures required for accept/reject decisions if the true MTBF of the equipment is equal to either:

T_c : the contractual MTBF requirement, or

T_m : the "absolute minimum" MTBF requirement

E(X), the most probable number of failures required if the true MTBF is X, is calculated for each of the values T_c and T_m in Attachment 3, first for Table I and then for Table A. Comparing these values with the corresponding tables we obtain the following results:

	TABLE I	TABLE A
T_c*	6.34	3.45
T_m*	4.01	1.38

where the figures shown are in multiples of contract MTBF[1] and

T_c* = the average time units for acceptance if the true MTBF is equal to T_c (the contractual MTBF requirement)

T_m* = the average time units for rejection if the true MTBF is equal to T_m (1/2 the contractual MTBF requirement)

These figures show that, on the average, testing via Table A will be completed in less than half the time required by Table I. The impact of test time on the overall program must nevertheless be weighed against the risks that are involved. At any decision point, we decrease our confidence by about 5% when using Table A instead of Table I. In both cases our confidence is associated with having 1/2 the contractual MTBF requirement.

[1] To change T_c^* and T_m^* to actual test time, multiply the time units indicated by the contractual MTBF requirement.

CHAPTER 6

METHODS TO BE EMPLOYED IN FUTURE PROCUREMENTS

There is reason to believe that the authors of MIL-R-26474 realized the shortcomings of Table I, since they provided exceptions in the event that conditions required termination of testing prior to reaching an accept/reject decision. (See Conditions I and II of MIL-R-26474.) The specification provides that if 3 multiples of contract MTBF have been reached, and if the final reliability estimate is "clearly" greater than the contractual requirement, then an accept decision will be made. However, how much greater is "clearly" greater, and on what kind of data should the final reliability estimate be based, is not spelled out in the specification. For example, do we completely ignore the results of our (3 multiples of MTBF) testing that was accomplished? A provision such as this pre-supposes that the procuring agency was not able to develop an acceptance/rejectance criteria that would give a substantial level of confidence for shorter periods of testing (such as Table A). To illustrate the possible consequences of this condition, suppose that after 3 multiples of testing 7 relevant failures had occurred, and that the contractor's predictions were still higher than the contractual requirement. Under MIL-R-26474 the Air Force might be forced to accept the equipment, and at the staggering risk of 74%; that is, the probability that equipment having ½ the required MTBF would have 7 or less failures in 3 multiples of contractual MTBF is 74%. Yet, if Table A was in force, the equipment would be rejected with less than 7% risk to the contractor. In view of the above mentioned ambiguities and/or the unwarranted risks that could result, MIL-R-26474 should not be cited in future procurements, unless the specific accept/reject criteria is defined in the equipment specification or work statement giving the conditions that apply if termination of testing becomes necessary, and <u>only</u> after full consideration of the risks that may be involved. In addition, the work statement should call for a reliability demonstration plan which must clearly state the ground rules for counting failures and measuring operating time, as well as the operating conditions that will prevail during the demonstration.

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ATTACHMENTS 1 THROUGH 4

VERIFICATION OF QUANTITATIVE RELIABILITY REQUIREMENTS

Decision Criteria

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BASIC LAWS OF PROBABILITY

1. Underlying Assumption. The elements of set theory, wherein a point (element) is called an "outcome of an experiment", the collection of all points (outcomes) is called the "sample space" (and denoted by G), and any sub-collection of points (outcomes) of G is called an "event". In particular G is an event, and the collection consisting of no points (outcomes) is an event (called the "null event" and denoted by $\emptyset$). A "random variable" is a numerically-valued function defined over the sample space G; i.e., a rule which assigns exactly one number to each outcome.

2. Basic Axioms. We assume the existence of a function P satisfying the following axioms[1].

a. Axiom 1: $P\{G\} = 1$

b. Axiom 2: $P\{\emptyset\} = 0$

c. Axiom 3: $0 \leq P\{E\} \leq 1$ for any event E

d. Axiom 4: $P\{E_1 \cup E_2\} = P\{E_1\} + P\{E_2\} - P\{E_1 \cap E_2\}$

NOTE: If $\{E_1 \cap E_2\} = \emptyset$ then

$$P\{E_1 \cup E_2\} = P\{E_1\} + P\{E_2\}$$

3. Cumulative Distribution Function. For any random variable $X = X(w)$ the function defined by

$$F_X : F_X(a) = P\{X(w) \leq a\} \text{ where } (-\infty \leq a \leq \infty)$$

is called the cumulative distribution function.

4. Properties of the Cumulative Distribution Function. The cumulative distribution function has the following basic properties:

a. It is a non-decreasing function.

b. $F_X(-\infty) = 0$

c. $F_X(\infty) = 1$

[1] $P\{E\}$ is notation for "The (numerical) probability of the event E occurring". $\{E_1 \cap E_2\}$ signifies the simultaneous occurrence of E_1 and E_2. $\{E_1 \cup E_2\}$ is an event which occurs when either E_1 or E_2 occurs.

DERIVATION OF TABLE I, MIL-R-26474

Table I is derived through the use of the following formulas which were developed by mathematicians Epstein and Sobel[1]. We shall begin by defining:

α = Producer's Risk , β = AF Risk

T_c = Contractual MTBF requirement

T_m = Absolute minimum required MTBF

f_a = Number of failures for acceptance

f_r = Number of failures for rejectance

t_a = Test time for acceptance (ultimately expressed as a function of f_a)

t_r = Test time for rejectance (ultimately expressed as a function of f_r)

ln = Abbreviation for the natural logarithm function.

The equations we need are:

$$t_a = \frac{-\ln\left(\frac{\beta}{1-\alpha}\right) + (f_a)\ln\left(\frac{T_c}{T_m}\right)}{\frac{T_c - T_m}{T_m}}$$

$$t_r = \frac{-\ln\left(\frac{1-\beta}{\alpha}\right) + (f_r)\ln\left(\frac{T_c}{T_m}\right)}{\frac{T_c - T_m}{T_m}}$$

Now, to illustrate the use of these formulas, we first develop Table I in which,

(1) $\alpha = 10\% = .1$

(2) $\beta = 10\% = .1$

(3) $T_m = \frac{T_c}{2}$

[1] See AGREE (Advisory Group on Reliability of Electronic Equipment) Report, 4 June 1957, Supt of Documents, U. S. Government Printing Office, Wash 25, D. C.

Preliminary Calculations:

1. By (3), $\frac{T_c}{T_m} = 2$, and $\frac{T_c - T_m}{T_m} = 1$

2. By (1) and (2) and standard mathematical tables we get:

$$-\ln\left(\frac{\beta}{1-\alpha}\right) = -\ln\left(\frac{.1}{1-.1}\right) = -\ln\left(\frac{.1}{.9}\right) = -\ln\left(\frac{1}{9}\right) = \ln 9 = 2.2$$

$$-\ln\left(\frac{1-\beta}{\alpha}\right) = -\ln\left(\frac{1-.1}{.1}\right) = -\ln\left(\frac{.9}{.1}\right) = -\ln 9 = -2.2$$

$$\ln\left(\frac{T_c}{T_m}\right) = \ln 2 = .69$$

Now we make the appropriate substitutions giving us:

For Acceptance: $t_a = 2.2 + .69\, f_a$

For Rejectance: $t_r = -2.2 + .69\, f_r$

Next we simply solve these equations for numbers of failures = 0, 1, 2, etc.

f_a	t_a
0	2.20
1	2.89
2	3.58
3	4.27
4	4.96
5	5.65
6	6.34
7	7.03
8	7.72
9	8.41
10	9.10
11	9.79
12	10.48
13	11.17
14	11.86
15	12.55

f_r	t_r
0	− 2.20
1	− 1.51
2	− 0.82
3	− 0.13
4	0.56
5	1.25
6	1.94
7	2.63
8	3.32
9	4.01
10	4.70
11	5.39
12	6.08
13	6.77
14	7.46
15	7.72

Since the equations for acceptance/rejectance are straight lines with the same slope, the above lists could go on indefinitely (never reaching a point where the number of failures for acceptance is one less than the number of failures for rejectance, for the same test time; i.e., with $t_a = t_r$. However, it was shown in Chapter 3 that, as test time is increased, we

eventually reach a point where this occurs; i.e., the risks are comparable for acceptance/rejectance failures differing by one. Epstein[2], in fact, has developed formulas for finding a truncation point for which α = 10% and β never exceeds 10%. These formulas, when applied to Table I give a point of truncation of 10.30 time units with 15 failures for rejectance These were used by the writers of MIL-R-26474, but here again, the formulas have a limitation in that they do not find the earliest truncation point with α and β approximately equal to 10%. The earliest point would be 9.5 time units with 14 failures specified for rejectance. To see this more clearly, the end of Table I could have been established as follows, with risks as shown:

.	.	.	.	.	.
7.46	14	2%	8-13		
7.72	14	3%	9-13	8	3%
8.15	14	4%	9-13		
8.41	14	5%	10-13	9	3%
9.10	14	7%	11-13	10	3%
9.50	14	10%		13	10%

The authors of Table I also arbitrarily decided that testing less than three multiples of MTBF is a minimum requirement (in order to give some assurance that equipment with unduly short life will be rejected). Hence for $f_a = 1$, t_a is changed from 2.89 to 3.00 and a corresponding (arbitrary) allowance of $f_r = 8$ is made at 3.00 time units. From here on the computed values are used until reaching the 10.30 point.

Derivation of Table A. We define α, β, T_c, T_m, f_a, f_r, t_a, and t_r as before and use the same formulas:

$$t_a = \frac{-\ln\left(\frac{\beta}{1-\alpha}\right) + (f_a)\ln\left(\frac{T_c}{T_m}\right)}{\frac{T_c - T_m}{T_m}}$$

2 "Truncated Life Tests in the Exponential Case", B. Epstein, Annals of Mathematical Statistics, Vol 25, pp 555-564.

$$t_r = \frac{-\ln\left(\frac{1-\beta}{\alpha}\right) + (f_r)\ln\left(\frac{T_c}{T_m}\right)}{\frac{T_c - T_m}{T_m}}$$

But this time,

(1) α = 20% = .2

(2) β = 20% = .2

(3) $T_m = \frac{T_c}{2}$

PRELIMINARY CALCULATIONS:

1. By (3), $\frac{T_c}{T_m} = 2$ and $\frac{T_c - T_m}{T_m} = 1$

2. By (1) and (2) and Standard Mathematical Tables:

$$-\ln\left(\frac{\beta}{1-\alpha}\right) = -\ln\left(\frac{.2}{1-.2}\right) = -\ln\left(\frac{.2}{.8}\right) = -\ln\left(\frac{1}{4}\right) = \ln 4 = 1.386$$

$$-\ln\left(\frac{1-\beta}{\alpha}\right) = -\ln\left(\frac{1-.2}{.2}\right) = -\ln\left(\frac{.8}{.2}\right) = -\ln 4 = -1.386$$

$$\ln\left(\frac{T_c}{T_m}\right) = \ln 2 = .69$$

Making the appropriate substitutions:

Acceptance: $T_a = 1.38 + .69\, f_a$

Rejectance: $T_r = -1.38 + .69\, f_r$

Solving these for numbers of failures = 0, 1, 2,..etc.

f_a	t_a
0	1.38
1	2.07
2	2.76
3	3.45
4	4.14
5	4.83

f_r	t_r
0	-1.38
1	- .69
2	0
3	.69
4	1.38
5	2.07

f_a	t_a
6	5.52
7	6.21
8	6.90
9	7.59
10	8.28

f_r	t_r
6	2.76
7	3.45
8	4.14
9	4.83
10	5.52
11	6.21
12	6.90

An interesting feature of this table is that test times for acceptance/rejectance coincide (since the absolute value of the constant term is twice the slope). For this table we do not concern ourselves with setting an arbitrary minimum test time, since this table is designed for high MTBF requirements where the number of models available for testing is limited. Hence, we start our table at 1.38 time units. Now, if we used the formulas for truncation our table would look as follows:

1.38	4		1-3		0
2.07	5		2-4		1
2.76	6		3-5		2
3.45	7		4-6		3
4.14	7	12½%	5-6		4
4.73	7	20%	-	17%	6

with risks indicated. However, we have no desire to let the risks climb as high as 20% (producer) and 17% (AF). Therefore, we have arbitrarily extended our table to 8.0 time units. This point was selected by scanning the Poisson tables until reaching a point of comparable risks which are close to 10%. The derived table is included in Chapter 4 of this pamphlet showing the risks levels (11% and 12½%, respectively) which are reached.

DERIVATION OF AVERAGE TEST TIME FOR TABLE I AND TABLE A

First define

T_c = contract MTBF requirement

T_m = absolute minimum MTBF requirement

$r = \frac{T_c}{T_m}$

α = the producer's risk (maximum) used for obtaining sequential test formulas

β = the AF's risk (maximum) used for obtaining sequential test formulas.

We may now give formulas developed by Epstein and Sobel[1] for calculeting E (X), the most probable number of feilures required for e decision if the true MTBF of the equipment is X.

These formulas are as follows (where "ln" denotes the natural logarithm function):

$$E(T_c) \simeq \frac{(1-\alpha)\ln\left(\frac{\beta}{1-\alpha}\right) + \alpha \ln\left(\frac{1-\beta}{\alpha}\right)}{\ln r - (r-1)}$$

$$E(T_m) \simeq \frac{\beta \ln\left(\frac{\beta}{1-\alpha}\right) + (1-\beta)\ln\left(\frac{1-\beta}{\alpha}\right)}{\ln r - \left(\frac{r-1}{r}\right)}$$

Let's calculete E (T_c) and E (T_m) for Table I and Table A, approximating to whole numbers et the end since our answer must be "numbers of failures".

TABLE I

We heve $r = \frac{T_c}{T_m} = 2$, $\alpha = .10$, $\beta = .10$

Since $\ln\left(\frac{1}{9}\right) = -\ln 9$, we obtain

[1] "Sequential Life Tests in the Exponential Case", by B. Epstein and M. Sobel, Annals of Math. Stat., Mar 1955, pp 82-93.

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$$E(T_c) = \frac{(.9)(-\ln 9) + (.1)(\ln 9)}{(\ln 2)-(2-1)} = \frac{(.9)(-2.2) + (.1)(2.2)}{(.7)-1}$$

$$= \frac{-1.98 + .22}{-.3}$$

$$= \frac{1.76}{.3}$$

$$\simeq 6$$

$$E(T_m) = \frac{(.1)(-\ln 9) + (.9)(\ln 9)}{\ln 2 - \frac{(2-1)}{2}} = \frac{(.1)(-2.2) + (.9)(2.2)}{(.7) - (.5)}$$

$$= \frac{-.22 + 1.98}{.2}$$

$$= \frac{1.76}{.2}$$

$$\simeq 9$$

TABLE A

We have $r = \frac{T_c}{T_m} = 2$, $\alpha = .20$, $\beta = .20$

and $(1-\alpha) = .8$, $\frac{\beta}{1-\alpha} = \frac{1}{4}$, $\frac{1-\beta}{\alpha} = 4$.

Since $\ln \frac{1}{4} = -\ln 4$, we obtain

$$E(T_c) = \frac{(.8)(-\ln 4) + (.2)(\ln 4)}{(\ln 2) - (2-1)} = \frac{(.8)(-1.39) + (.2)(1.39)}{(.7) - 1}$$

$$= \frac{-1.112 + .278}{-.3}$$

$$= \frac{.834}{.3} \simeq 3$$

$$E(T_m) = \frac{(.2)(-\ln 4) + (.8)(\ln 4)}{\ln 2 - (\frac{2-1}{2})} = \frac{(.2)(-1.39) + (.8)(1.39)}{(.7) - (.5)}$$

$$= \frac{(-.278) + (1.112)}{.2}$$

$$= \frac{.834}{.2} \simeq 4$$

The calculated number of failures can be compared with Table I to obtain

T_c^* = the average time units for acceptance if the true MTBF is equal to the contract MTBF

T_m^* = the average time units for rejectance if the true MTBF is 1/2 the contract MTBF

These are

$T_c^* = 6.34$

$T_m^* = 4.01$

The calculated number of failures can be compared with Table A to obtain

$T_c^* = 3.45$

$T_m^* = 1.38$

Now comparison of T_c^* and T_m^* for Table I and Table A is readily seen by the following table:

	TABLE I	TABLE A
T_c^*	6.34	3.45
T_m^*	4.01	1.38

which shows that average test time[2] using Table A is less than half that of Table I. Yet, our confidence is reduced only by about 3-7% (During early stages of testing acceptance is made with 90% confidence instead of 97%, whereas if testing is carried to the end of the tables, acceptance is made with 87½% confidence instead of 91%).

[2] To convert "time units" to "test time" simply multiply the time units by the contract MTBF requirement.

TABLE OF THE POISSON DISTRIBUTION[1]

U = 0.10

X	P(X)	C(X)	D(X)
0	0.905	0.905	1.000
1	0.090	0.995	0.095
2	0.005	1.000	0.005

U = 0.15

X	P(X)	C(X)	D(X)
0	0.861	0.861	1.000
1	0.129	0.990	0.139
2	0.010	0.999	0.010
3	0.000	1.000	0.001

U = 0.20

X	P(X)	C(X)	D(X)
0	0.819	0.819	1.000
1	0.164	0.982	0.181
2	0.016	0.999	0.018
3	0.001	1.000	0.001

U = 0.25

X	P(X)	C(X)	D(X)
0	0.779	0.779	1.000
1	0.195	0.974	0.221

NOTE: For certain applicetions of the Poisson Distribution, valuea auch es C(2) = 1.000 would be erroneoua even if the equal aign waa changed to "approximately equal" (≃). Thia is a consequence of rounding at three decimal placae.

[1]The table wes computed on a Philco 2000 computer (Model 212) at ESD Space Track Facility. The program is on fila et the OPR. Saa page 12 for definitions of U, P(X), C(X), and D(X).

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X	P(X)	C(X)	D(X)
	0.024	0.998	0.026
	0.002	1.000	0.002

U= 0.30

X	P(X)	C(X)	D(X)
0	0.741	0.741	1.000
1	0.222	0.963	0.259
2	0.033	0.996	0.037
3	0.003	1.000	0.004

U= 0.35

X	P(X)	C(X)	D(X)
0	0.705	0.705	1.000
1	0.247	0.951	0.295
2	0.043	0.994	0.049
3	0.005	1.000	0.006

U= 0.40

X	P(X)	C(X)	D(X)
0	0.670	0.670	1.000
1	0.268	0.938	0.330
2	0.054	0.992	0.062
3	0.007	0.999	0.008
4	0.001	1.000	0.001

U= 0.45

X	P(X)	C(X)	D(X)
0	0.638	0.638	1.000

X	P(X)	C(X)	D(X)
1	0.287	0.925	0.362
2	0.065	0.989	0.075
3	0.010	0.999	0.011
4	0.001	1.000	0.001

U= 0.50

X	P(X)	C(X)	D(X)
0	0.607	0.607	1.000
1	0.303	0.910	0.393
2	0.076	0.986	0.090
3	0.013	0.998	0.014
4	0.002	1.000	0.002

U= 0.55

X	P(X)	C(X)	D(X)
0	0.577	0.577	1.000
1	0.317	0.894	0.423
2	0.087	0.982	0.106
3	0.016	0.998	0.018
4	0.002	1.000	0.002

U= 0.60

X	P(X)	C(X)	D(X)
0	0.549	0.549	1.000
1	0.329	0.878	0.451
2	0.099	0.977	0.122
3	0.020	0.997	0.023
4	0.003	1.000	0.003

U= 0.65

X	P(X)	C(X)	D(X)
0	0.522	0.522	1.000
1	0.339	0.861	0.478
2	0.110	0.972	0.139
3	0.024	0.996	0.028
4	0.004	0.999	0.004
5	0.001	1.000	0.001

U= 0.70

X	P(X)	C(X)	D(X)
0	0.497	0.497	1.000
1	0.348	0.844	0.503
2	0.122	0.966	0.156
3	0.028	0.994	0.034
4	0.005	0.999	0.006
5	0.001	1.000	0.001

U= 0.75

X	P(X)	C(X)	D(X)
0	0.472	0.472	1.000
1	0.354	0.827	0.528
2	0.133	0.959	0.173
3	0.033	0.993	0.041
4	0.006	0.999	0.007
5	0.001	1.000	0.001

U= 0.80

X	P(X)	C(X)	D(X)
0	0.449	0.449	1.000
1	0.359	0.809	0.551
2	0.144	0.953	0.191
3	0.038	0.991	0.047

X	P(X)	C(X)	D(X)
4	0.008	0.999	0.009
5	0.001	1.000	0.001

U= 0.85

X	P(X)	C(X)	D(X)
0	0.427	0.427	1.000
1	0.363	0.791	0.573
2	0.154	0.945	0.209
3	0.044	0.989	0.055
4	0.009	0.998	0.011
5	[illegible]	1.000	0.002

U= 0.90

X	P(X)	C(X)	D(X)
0	0.407	0.407	1.000
1	0.366	0.772	0.593
2	0.165	0.937	0.228
3	0.049	0.987	0.063
4	0.011	0.998	0.013
5	0.002	1.000	0.002

U= 0.95

X	P(X)	C(X)	D(X)
0	0.387	0.387	1.000
1	0.367	0.754	0.613
2	0.175	0.929	0.246
3	0.055	0.984	0.071
4	0.013	0.997	0.016
5	0.002	1.000	0.003

U= 1.00

X	P(X)	C(X)	D(X)
0	0.368	0.368	1.000
1	0.368	0.736	0.632
2	0.184	0.920	0.264
3	0.061	0.981	0.080
4	0.015	0.996	0.019
5	0.003	0.999	0.004
6	0.001	1.000	0.001

U= 1.05

X	P(X)	C(X)	D(X)
0	0.350	0.350	1.000
1	0.367	0.717	0.650
2	0.193	0.910	0.283
3	0.068	0.978	0.090
4	0.018	0.996	0.022
5	0.004	0.999	0.004
6	0.001	1.000	0.001

U= 1.10

X	P(X)	C(X)	D(X)
0	0.333	0.333	1.000
1	0.366	0.699	0.667
2	0.201	0.900	0.301
3	0.074	0.974	0.100
4	0.020	0.995	0.026
5	0.004	0.999	0.005
6	0.001	1.000	0.001

U= 1.15

X	P(X)	C(X)	D(X)
0	0.317	0.317	1.000

X	P(X)	C(X)	D(X)
1	0.364	0.681	0.683
2	0.209	0.890	0.319
3	0.080	0.970	0.110
4	0.023	0.993	0.030
5	0.005	0.999	0.007
6	0.001	1.000	0.001

U= 1.20

X	P(X)	C(X)	D(X)
0	0.301	0.301	1.000
1	0.361	0.663	0.699
2	0.217	0.879	0.337
3	0.087	0.966	0.121
4	0.026	0.992	0.034
5	0.006	0.998	0.008
6	0.001	1.000	0.002

U= 1.25

X	P(X)	C(X)	D(X)
0	0.287	0.287	1.000
1	0.358	0.645	0.713
2	0.224	0.868	0.355
3	0.093	0.962	0.132
4	0.029	0.991	0.038
5	0.007	0.998	0.009
6	0.002	1.000	0.002

U= 1.30

X	P(X)	C(X)	D(X)
0	0.273	0.273	1.000
1	0.354	0.627	0.727
2	0.230	0.857	0.373
3	0.100	0.957	0.143

X	P(X)	C(X)	D(X)
4	0.032	0.989	0.043
5	0.008	0.998	0.011
6	0.002	1.000	0.002

U= 1.35

X	P(X)	C(X)	D(X)
0	0.259	0.259	1.000
1	0.350	0.609	0.741
2	0.236	0.845	0.391
3	0.106	0.952	0.155
4	0.036	0.988	0.048
5	0.010	0.997	0.012
6	0.002	0.999	0.003
7	0.000	1.000	0.001

U= 1.40

X	P(X)	C(X)	D(X)
0	0.247	0.247	1.000
1	0.345	0.592	0.753
2	0.242	0.833	0.408
3	0.113	0.946	0.167
4	0.039	0.986	0.054
5	0.011	0.997	0.014
6	0.003	0.999	0.003
7	0.001	1.000	0.001

U= 1.45

X	P(X)	C(X)	D(X)
0	0.235	0.235	1.000
1	0.340	0.575	0.765
2	0.247	0.821	0.425
3	0.119	0.940	0.179
4	0.043	0.984	0.060

X	P(X)	C(X)	D(X)
5	0.013	0.996	0.016
6	0.003	0.999	0.004
7	0.001	1.000	0.001

U= 1.50

X	P(X)	C(X)	D(X)
0	0.223	0.223	1.000
1	0.335	0.558	0.777
2	0.251	0.809	0.442
3	0.126	0.934	0.191
4	0.047	0.981	0.066
5	0.014	0.996	0.019
6	0.004	0.999	0.004
7	0.001	1.000	0.001

U= 1.55

X	P(X)	C(X)	D(X)
0	0.212	0.212	1.000
1	0.329	0.541	0.788
2	0.255	0.796	0.459
3	0.132	0.928	0.204
4	0.051	0.979	0.072
5	0.016	0.995	0.021
6	0.004	0.999	0.005
7	0.001	1.000	0.001

U= 1.60

X	P(X)	C(X)	D(X)
0	0.202	0.202	1.000
1	0.323	0.525	0.798
2	0.258	0.783	0.475
3	0.138	0.921	0.217
4	0.055	0.976	0.079

X	P(X)	C(X)	D(X)
5	0.018	0.994	0.024
6	0.005	0.999	0.006
7	0.001	1.000	0.001

U= 1.65

X	P(X)	C(X)	D(X)
0	0.192	0.192	1.000
1	0.317	0.509	0.808
2	0.261	0.770	0.491
3	0.144	0.914	0.230
4	0.059	0.973	0.086
5	0.020	0.993	0.027
6	0.005	0.998	0.007
7	0.001	1.000	0.002

U= 1.70

X	P(X)	C(X)	D(X)
0	0.183	0.183	1.000
1	0.311	0.493	0.817
2	0.264	0.757	0.507
3	0.150	0.907	0.243
4	0.064	0.970	0.093
5	0.022	0.992	0.030
6	0.006	0.998	0.008
7	0.001	1.000	0.002

U= 1.75

X	P(X)	C(X)	D(X)
0	0.174	0.174	1.000
1	0.304	0.478	0.826
2	0.266	0.744	0.522
3	0.155	0.899	0.256
4	0.068	0.967	0.101

X	P(X)	C(X)	D(X)
5	0.024	0.991	0.033
6	0.007	0.998	0.009
7	0.002	1.000	0.002

U= 1.80

X	P(X)	C(X)	D(X)
0	0.165	0.165	1.000
1	0.298	0.463	0.835
2	0.268	0.731	0.537
3	0.161	0.891	0.269
4	0.072	0.964	0.109
5	0.026	0.990	0.036
6	0.008	0.997	0.010
7	0.002	0.999	0.003
8	0.000	1.000	0.001

U= 1.85

X	P(X)	C(X)	D(X)
0	0.157	0.157	1.000
1	0.291	0.448	0.843
2	0.269	0.717	0.552
3	0.166	0.883	0.283
4	0.077	0.960	0.117
5	0.028	0.988	0.040
6	0.009	0.997	0.012
7	0.002	0.999	0.003
8	0.001	1.000	0.001

U= 1.90

X	P(X)	C(X)	D(X)
0	0.150	0.150	1.000
1	0.284	0.434	0.850
2	0.270	0.704	0.566

X	P(X)	C(X)	D(X)
3	0.171	0.875	0.296
4	0.081	0.956	0.125
5	0.031	0.987	0.044
6	0.010	0.997	0.013
7	0.003	0.999	0.003
8	0.001	1.000	0.001

U= 1.95

X	P(X)	C(X)	D(X)
0	0.142	0.142	1.000
1	0.277	0.420	0.858
2	0.270	0.690	0.580
3	0.176	0.866	0.310
4	0.086	0.952	0.134
5	0.033	0.985	0.048
6	0.011	0.996	0.015
7	0.003	0.999	0.004
8	0.001	1.000	0.001

U= 2.00

X	P(X)	C(X)	D(X)
0	0.135	0.135	1.000
1	0.271	0.406	0.865
2	0.271	0.677	0.594
3	0.180	0.857	0.323
4	0.090	0.947	0.143
5	0.036	0.983	0.053
6	0.012	0.995	0.017
7	0.003	0.999	0.005
8	0.001	1.000	0.001

U= 2.10

X	P(X)	C(X)	D(X)
0	0.122	0.122	1.000
1	0.257	0.380	0.878
2	0.270	0.650	0.620
3	0.189	0.839	0.350
4	0.099	0.938	0.161
5	0.042	0.980	0.062
6	0.015	0.994	0.020
7	0.004	0.999	0.006
8	0.001	1.000	0.001

U= 2.20

X	P(X)	C(X)	D(X)
0	0.111	0.111	1.000
1	0.244	0.355	0.889
2	0.268	0.623	0.645
3	0.197	0.819	0.377
4	0.108	0.928	0.181
5	0.048	0.975	0.072
6	0.017	0.993	0.025
7	0.005	0.998	0.007
8	0.002	1.000	0.002

U= 2.30

X	P(X)	C(X)	D(X)
0	0.100	0.100	1.000
1	0.231	0.331	0.900
2	0.265	0.596	0.669
3	0.203	0.799	0.404
4	0.117	0.916	0.201
5	0.054	0.970	0.084
6	0.021	0.991	0.030
7	0.007	0.997	0.009
8	0.002	0.999	0.003
9	0.000	1.000	0.001

U= 2.40

X	P(X)	C(X)	D(X)
0	0.091	0.091	1.000
1	0.218	0.308	0.909
2	0.261	0.570	0.692
3	0.209	0.779	0.430
4	0.125	0.904	0.221
5	0.060	0.964	0.096
6	0.024	0.988	0.036
7	0.008	0.997	0.012
8	0.002	0.999	0.003
9	0.001	1.000	0.001

U= 2.50

X	P(X)	C(X)	D(X)
0	0.082	0.082	1.000
1	0.205	0.287	0.918
2	0.257	0.544	0.713
3	0.214	0.758	0.456
4	0.134	0.891	0.242
5	0.067	0.958	0.109
6	0.028	0.986	0.042
7	0.010	0.996	0.014
8	0.003	0.999	0.004
9	0.001	1.000	0.001

U= 2.60

X	P(X)	C(X)	D(X)
0	0.074	0.074	1.000
1	0.193	0.267	0.926
2	0.251	0.518	0.733
3	0.218	0.736	0.482
4	0.141	0.877	0.264
5	0.074	0.951	0.123
6	0.032	0.983	0.049
7	0.012	0.995	0.017
8	0.004	0.999	0.005
9	0.001	1.000	0.001

U= 2.70

X	P(X)	C(X)	D(X)
0	0.067	0.067	1.000
1	0.181	0.249	0.933
2	0.245	0.494	0.751
3	0.220	0.714	0.506
4	0.149	0.863	0.286
5	0.080	0.943	0.137
6	0.036	0.979	0.057
7	0.014	0.993	0.021
8	0.005	0.998	0.007
9	0.001	0.999	0.002
10	0.000	1.000	0.001

U= 2.80

X	P(X)	C(X)	D(X)
0	0.061	0.061	1.000
1	0.170	0.231	0.939
2	0.238	0.469	0.769
3	0.222	0.692	0.531
4	0.156	0.848	0.308
5	0.087	0.935	0.152
6	0.041	0.976	0.065
7	0.016	0.992	0.024
8	0.006	0.998	0.008
9	0.002	0.999	0.002
10	0.000	1.000	0.001

U= 2.90

X	P(X)	C(X)	D(X)
0	0.055	0.055	1.000
1	0.160	0.215	0.945
2	0.231	0.446	0.785
3	0.224	0.670	0.554
4	0.162	0.832	0.330
5	0.094	0.926	0.168
6	0.045	0.971	0.074
7	0.019	0.990	0.029

X	P(X)	C(X)	D(X)
8	0.007	0.997	0.010
9	0.002	0.999	0.003
10	0.001	1.000	0.001

U= 3.00

X	P(X)	C(X)	D(X)
0	0.050	0.050	1.000
1	0.149	0.199	0.950
2	0.224	0.423	0.801
3	0.224	0.647	0.577
4	0.168	0.815	0.353
5	0.101	0.916	0.185
6	0.050	0.966	0.084
7	0.022	0.988	0.034
8	0.008	0.996	0.012
9	0.003	0.999	0.004
10	0.001	1.000	0.001

U= 3.10

X	P(X)	C(X)	D(X)
0	0.045	0.045	1.000
1	0.140	0.185	0.955
2	0.216	0.401	0.815
3	0.224	0.625	0.599
4	0.173	0.798	0.375
5	0.107	0.906	0.202
6	0.056	0.961	0.094
7	0.025	0.986	0.039
8	0.010	0.995	0.014
9	0.003	0.999	0.005
10	0.001	1.000	0.001

U= 3.20

X	P(X)	C(X)	D(X)
0	0.041	0.041	1.000
1	0.130	0.171	0.959
2	0.209	0.380	0.829
3	0.223	0.603	0.620
4	0.178	0.781	0.397
5	0.114	0.895	0.219
6	0.061	0.955	0.105
7	0.028	0.983	0.045
8	0.011	0.994	0.017
9	0.004	0.998	0.006
10	0.001	1.000	0.002

U= 3.30

X	P(X)	C(X)	D(X)
0	0.037	0.037	1.000
1	0.122	0.159	0.963
2	0.201	0.359	0.841
3	0.221	0.580	0.641
4	0.182	0.763	0.420
5	0.120	0.883	0.237
6	0.066	0.949	0.117
7	0.031	0.980	0.051
8	0.013	0.993	0.020
9	0.005	0.998	0.007
10	0.002	0.999	0.002
11	0.000	1.000	0.001

U= 3.40

X	P(X)	C(X)	D(X)
0	0.033	0.033	1.000
1	0.113	0.147	0.967
2	0.193	0.340	0.853
3	0.219	0.558	0.660
4	0.186	0.744	0.442
5	0.126	0.871	0.256
6	0.072	0.942	0.129

X	P(X)	C(X)	D(X)
7	0.035	0.977	0.058
8	0.015	0.992	0.023
9	0.006	0.997	0.008
10	0.002	0.999	0.003
11	0.001	1.000	0.001

U= 3.50

X	P(X)	C(X)	D(X)
0	0.030	0.030	1.000
1	0.106	0.136	0.970
2	0.185	0.321	0.864
3	0.216	0.537	0.679
4	0.189	0.725	0.463
5	0.132	0.858	0.275
6	0.077	0.935	0.142
7	0.039	0.973	0.065
8	0.017	0.990	0.027
9	0.007	0.997	0.010
10	0.002	0.999	0.003
11	0.001	1.000	0.001

U= 3.60

X	P(X)	C(X)	D(X)
0	0.027	0.027	1.000
1	0.098	0.126	0.973
2	0.177	0.303	0.874
3	0.212	0.515	0.697
4	0.191	0.706	0.485
5	0.138	0.844	0.294
6	0.083	0.927	0.156
7	0.042	0.969	0.073
8	0.019	0.988	0.031
9	0.008	0.996	0.012
10	0.003	0.999	0.004
11	0.001	1.000	0.001

U= 3.70

X	P(X)	C(X)	D(X)
[illegible]	0.025	0.025	1.000
[illegible]	0.091	0.116	0.975
2	0.169	0.285	0.884
3	0.209	0.494	0.715
4	0.193	0.687	0.506
[illegible]	0.143	0.830	0.313
[illegible]	0.088	0.918	0.170
[illegible]	0.047	0.965	0.082
[illegible]	0.022	0.986	0.035
[illegible]	0.009	0.995	0.014
[illegible]	0.003	0.998	0.005
1	0.001	1.000	0.002

U= 3.80

X	P(X)	C(X)	D(X)
0	0.022	0.022	1.000
1	0.085	0.107	0.978
2	0.162	0.269	0.893
3	0.205	0.473	0.731
4	0.194	0.668	0.527
5	0.148	0.816	0.332
6	0.094	0.909	0.184
7	0.051	0.960	0.091
8	0.024	0.984	0.040
9	0.010	0.994	0.016
10	0.004	0.998	0.006
11	0.001	0.999	0.002
12	0.000	1.000	0.001

U= 3.90

X	P(X)	C(X)	D(X)
0	0.020	0.020	1.000
1	0.079	0.099	0.980
2	0.154	0.253	0.901
3	0.200	0.453	0.747
4	0.195	0.648	0.547

X	P(X)	C(X)	D(X)
5	0.152	0.801	0.352
6	0.099	0.899	0.199
7	0.055	0.955	0.101
8	0.027	0.981	0.045
9	0.012	0.993	0.019
10	0.005	0.998	0.007
11	0.002	0.999	0.002
12	0.001	1.000	0.001

U= 4.00

X	P(X)	C(X)	D(X)
0	0.018	0.018	1.000
1	0.073	0.092	0.982
2	0.147	0.238	0.908
3	0.195	0.433	0.762
4	0.195	0.629	0.567
5	0.156	0.785	0.371
6	0.104	0.889	0.215
7	0.060	0.949	0.111
8	0.030	0.979	0.051
9	0.013	0.992	0.021
10	0.005	0.997	0.008
11	0.002	0.999	0.003
12	0.001	1.000	0.001

U= 4.10

X	P(X)	C(X)	D(X)
0	0.017	0.017	1.000
1	0.068	0.085	0.983
2	0.139	0.224	0.915
3	0.190	0.414	0.776
4	0.195	0.609	0.586
5	0.160	0.769	0.391
6	0.109	0.879	0.231
7	0.064	0.943	0.121
8	0.033	0.976	0.057
9	0.015	0.990	0.024
10	0.006	0.997	0.010

U= 4.40

X	P(X)	C(X)	D(X)
0	0.012	0.012	1.000
1	0.054	0.066	0.988
2	0.119	0.185	0.934
3	0.174	0.359	0.815
4	0.192	0.551	0.641
5	0.169	0.720	0.449
6	0.124	0.844	0.280
7	0.078	0.921	0.156
8	0.043	0.964	0.079
9	0.021	0.985	0.036
10	0.009	0.994	0.015
11	0.004	0.998	0.006
12	0.001	0.999	0.002
13	0.000	1.000	0.001

U= 4.50

X	P(X)	C(X)	D(X)
0	0.011	0.011	1.000
1	0.050	0.061	0.989
2	0.112	0.174	0.939
3	0.169	0.342	0.826
4	0.190	0.532	0.658
5	0.171	0.703	0.468
6	0.128	0.831	0.297
7	0.082	0.913	0.169
8	0.046	0.960	0.087
9	0.023	0.983	0.040
10	0.010	0.993	0.017
11	0.004	0.998	0.007
12	0.002	0.999	0.002
13	0.001	1.000	0.001

U= 4.60

X	P(X)	C(X)	D(X)
0	0.010	0.010	1.000
1	0.046	0.056	0.990

X	P(X)	C(X)	D(X)
11	0.002	0.999	0.003
12	0.001	1.000	0.001

U= 4.20

X	P(X)	C(X)	D(X)
0	0.015	0.015	1.000
1	0.063	0.078	0.985
2	0.132	0.210	0.922
3	0.185	0.395	0.790
4	0.194	0.590	0.605
5	0.163	0.753	0.410
6	0.114	0.867	0.247
7	0.069	0.936	0.133
8	0.036	0.972	0.064
9	0.017	0.989	0.028
10	0.007	0.996	0.011
11	0.003	0.999	0.004
12	0.001	1.000	0.001

U= 4.30

X	P(X)	C(X)	D(X)
0	0.014	0.014	1.000
1	0.058	0.072	0.986
2	0.125	0.197	0.928
3	0.180	0.377	0.803
4	0.193	0.570	0.623
5	0.166	0.737	0.430
6	0.119	0.856	0.263
7	0.073	0.929	0.144
8	0.039	0.968	0.071
9	0.019	0.987	0.032
10	0.008	0.995	0.013
11	0.003	0.998	0.005
12	0.001	0.999	0.002
13	0.000	1.000	0.001

	P(X)	C(X)	D(X)
2	0.106	0.163	0.944
3	0.163	0.326	0.837
4	0.188	0.513	0.674
5	0.173	0.686	0.487
6	0.132	0.818	0.314
7	0.087	0.905	0.182
8	0.050	0.955	0.095
9	0.026	0.980	0.045
10	0.012	0.992	0.020
11	0.005	0.997	0.008
12	0.002	0.999	0.003
13	0.001	1.000	0.001

U= 4.70

X	P(X)	C(X)	D(X)
0	0.009	0.009	1.000
1	0.043	0.052	0.991
2	0.100	0.152	0.948
3	0.157	0.310	0.848
4	0.185	0.495	0.690
5	0.174	0.668	0.505
6	0.136	0.805	0.332
7	0.091	0.896	0.195
8	0.054	0.950	0.104
9	0.028	0.978	0.050
10	0.013	0.991	0.022
11	0.006	0.997	0.009
12	0.002	0.999	0.003
13	0.001	1.000	0.001

U= 4.80

X	P(X)	C(X)	D(X)
0	0.008	0.008	1.000
1	0.040	0.048	0.992
2	0.095	0.143	0.952
3	0.152	0.294	0.857
4	0.182	0.476	0.706
5	0.175	0.651	0.524

X	P(X)	C(X)	D(X)
6	0.140	0.791	0.349
7	0.096	0.887	0.209
8	0.058	0.944	0.113
9	0.031	0.975	0.056
10	0.015	0.990	0.025
11	0.006	0.996	0.010
12	0.003	0.999	0.004
13	0.001	1.000	0.001

U= 4.90

X	P(X)	C(X)	D(X)
0	0.007	0.007	1.000
1	0.036	0.044	0.993
2	0.089	0.133	0.956
3	0.146	0.279	0.867
4	0.179	0.458	0.721
5	0.175	0.634	0.542
6	0.143	0.777	0.366
7	0.100	0.877	0.223
8	0.061	0.938	0.123
9	0.033	0.972	0.062
10	0.016	0.988	0.028
11	0.007	0.995	0.012
12	0.003	0.998	0.005
13	0.001	0.999	0.002
14	0.000	1.000	0.001

U= 5.00

X	P(X)	C(X)	D(X)
0	0.007	0.007	1.000
1	0.034	0.040	0.993
2	0.084	0.125	0.960
3	0.140	0.265	0.875
4	0.175	0.440	0.735
5	0.175	0.616	0.560
6	0.146	0.762	0.384
7	0.104	0.867	0.238
8	0.065	0.932	0.133

X	P(X)	C(X)	D(X)
9	0.036	0.968	0.068
10	0.018	0.986	0.032
11	0.008	0.995	0.014
12	0.003	0.998	0.005
13	0.001	0.999	0.002
14	0.000	1.000	0.001

U= 5.10

X	P(X)	C(X)	D(X)
0	0.006	0.006	1.000
1	0.031	0.037	0.994
2	0.079	0.116	0.963
3	0.135	0.251	0.884
4	0.172	0.423	0.749
5	0.175	0.598	0.577
6	0.149	0.747	0.402
7	0.109	0.856	0.253
8	0.069	0.925	0.144
9	0.039	0.964	0.075
10	0.020	0.984	0.036
11	0.009	0.994	0.016
12	0.004	0.998	0.006
13	0.002	0.999	0.002
14	0.001	1.000	0.001

U= 5.20

X	P(X)	C(X)	D(X)
0	0.006	0.006	1.000
1	0.029	0.034	0.994
2	0.075	0.109	0.966
3	0.129	0.238	0.891
4	0.168	0.406	0.762
5	0.175	0.581	0.594
6	0.151	0.732	0.419
7	0.113	0.845	0.268
8	0.073	0.918	0.155
9	0.042	0.960	0.082
10	0.022	0.982	0.040

x	P(X)	C(X)	D(X)
11	0.010	0.993	0.018
12	0.005	0.997	0.007
13	0.002	0.999	0.003
14	0.001	1.000	0.001

U= 5.30

X	P(X)	C(X)	D(X)
0	0.005	0.005	1.000
1	0.026	0.031	0.995
2	0.070	0.102	0.969
3	0.124	0.225	0.898
4	0.164	0.390	0.775
5	0.174	0.563	0.610
6	0.154	0.717	0.437
7	0.116	0.833	0.283
8	0.077	0.911	0.167
9	0.045	0.956	0.089
10	0.024	0.980	0.044
11	0.012	0.992	0.020
12	0.005	0.997	0.008
13	0.002	0.999	0.003
14	0.001	1.000	0.001

U= 5.40

X	P(X)	C(X)	D(X)
0	0.005	0.005	1.000
1	0.024	0.029	0.995
2	0.066	0.095	0.971
3	0.119	0.213	0.905
4	0.160	0.373	0.787
5	0.173	0.546	0.627
6	0.156	0.702	0.454
7	0.120	0.822	0.298
8	0.081	0.903	0.178
9	0.049	0.951	0.097
10	0.026	0.977	0.049
11	0.013	0.990	0.023
12	0.006	0.996	0.010

x	P(X)	C(X)	D(X)
13	0.002	0.999	0.004
14	0.001	1.000	0.001

U= 5.50

X	P(X)	C(X)	D(X)
0	0.004	0.004	1.000
1	0.022	0.027	0.996
2	0.062	0.088	0.973
3	0.113	0.202	0.912
4	0.156	0.358	0.798
5	0.171	0.529	0.642
6	0.157	0.686	0.471
7	0.123	0.809	0.314
8	0.085	0.894	0.191
9	0.052	0.946	0.106
10	0.029	0.975	0.054
11	0.014	0.989	0.025
12	0.007	0.996	0.011
13	0.003	0.998	0.004
14	0.001	0.999	0.002
15	0.000	1.000	0.001

U= 5.60

X	P(X)	C(X)	D(X)
0	0.004	0.004	1.000
1	0.021	0.024	0.996
2	0.058	0.082	0.976
3	0.108	0.191	0.918
4	0.152	0.342	0.809
5	0.170	0.512	0.658
6	0.158	0.670	0.488
7	0.127	0.797	0.330
8	0.089	0.886	0.203
9	0.055	0.941	0.114
10	0.031	0.972	0.059
11	0.016	0.988	0.028
12	0.007	0.995	0.012
13	0.003	0.998	0.005

X	P(X)	C(X)	D(X)
14	0.001	0.999	0.002
15	0.000	1.000	0.001

U= 5.70

X	P(X)	C(X)	D(X)
0	0.003	0.003	1.000
1	0.019	0.022	0.997
2	0.054	0.077	0.978
3	0.103	0.180	0.923
4	0.147	0.327	0.820
5	0.168	0.495	0.673
6	0.159	0.654	0.505
7	0.130	0.784	0.346
8	0.092	0.877	0.216
9	0.059	0.935	0.123
10	0.033	0.969	0.065
11	0.017	0.986	0.031
12	0.008	0.994	0.014
13	0.004	0.998	0.006
14	0.001	0.999	0.002
15	0.001	1.000	0.001

U= 5.80

X	P(X)	C(X)	D(X)
0	0.003	0.003	1.000
1	0.018	0.021	0.997
2	0.051	0.072	0.979
3	0.098	0.170	0.928
4	0.143	0.313	0.830
5	0.166	0.478	0.687
6	0.160	0.638	0.522
7	0.133	0.771	0.362
8	0.096	0.867	0.229
9	0.062	0.929	0.133
10	0.036	0.965	0.071
11	0.019	0.984	0.035
12	0.009	0.993	0.016
13	0.004	0.997	0.007

X	P(X)	C(X)	D(X)
14	0.002	0.999	0.003
15	0.001	1.000	0.001

U= 5.90

X	P(X)	C(X)	D(X)
0	0.003	0.003	1.000
1	0.016	0.019	0.997
2	0.048	0.067	0.981
3	0.094	0.160	0.933
4	0.138	0.299	0.840
5	0.163	0.462	0.701
6	0.160	0.622	0.538
7	0.135	0.758	0.378
8	0.100	0.857	0.242
9	0.065	0.923	0.143
10	0.039	0.961	0.077
11	0.021	0.982	0.039
12	0.010	0.992	0.018
13	0.005	0.997	0.008
14	0.002	0.999	0.003
15	0.001	1.000	0.001

U= 6.00

X	P(X)	C(X)	D(X)
0	0.002	0.002	1.000
1	0.015	0.017	0.998
2	0.045	0.062	0.983
3	0.089	0.151	0.938
4	0.134	0.285	0.849
5	0.161	0.446	0.715
6	0.161	0.606	0.554
7	0.138	0.744	0.394
8	0.103	0.847	0.256
9	0.069	0.916	0.153
10	0.041	0.957	0.084
11	0.023	0.980	0.043
12	0.011	0.991	0.020
13	0.005	0.996	0.009

X	P(X)	C(X)	D(X)
14	0.002	0.999	0.004
15	0.001	0.999	0.001
16	0.000	1.000	0.001

U= 6.50

X	P(X)	C(X)	D(X)
0	0.002	0.002	1.000
1	0.010	0.011	0.998
2	0.032	0.043	0.989
3	0.069	0.112	0.957
4	0.112	0.224	0.888
5	0.145	0.369	0.776
6	0.157	0.527	0.631
7	0.146	0.673	0.473
8	0.119	0.792	0.327
9	0.086	0.877	0.208
10	0.056	0.933	0.123
11	0.033	0.966	0.067
12	0.018	0.984	0.034
13	0.009	0.993	0.016
14	0.004	0.997	0.007
15	0.002	0.999	0.003
16	0.001	1.000	0.001

U= 7.00

X	P(X)	C(X)	D(X)
0	0.001	0.001	1.000
1	0.006	0.007	0.999
2	0.022	0.030	0.993
3	0.052	0.082	0.970
4	0.091	0.173	0.918
5	0.128	0.301	0.827
6	0.149	0.450	0.699
7	0.149	0.599	0.550
8	0.130	0.729	0.401
9	0.101	0.830	0.271
10	0.071	0.901	0.170
11	0.045	0.947	0.099

X	P(X)	C(X)	D(X)
12	0.026	0.973	0.053
13	0.014	0.987	0.027
14	0.007	0.994	0.013
15	0.003	0.998	0.006
16	0.001	0.999	0.002
17	0.001	1.000	0.001

U= 7.50

X	P(X)	C(X)	D(X)
0	0.001	0.001	1.000
1	0.004	0.005	0.999
2	0.016	0.020	0.995
3	0.039	0.059	0.980
4	0.073	0.132	0.941
5	0.109	0.241	0.868
6	0.137	0.378	0.759
7	0.146	0.525	0.622
8	0.137	0.662	0.475
9	0.114	0.776	0.338
10	0.086	0.862	0.224
11	0.059	0.921	0.138
12	0.037	0.957	0.079
13	0.021	0.978	0.043
14	0.011	0.990	0.022
15	0.006	0.995	0.010
16	0.003	0.998	0.005
17	0.001	0.999	0.002
18	0.000	1.000	0.001

U= 8.00

X	P(X)	C(X)	D(X)
1	0.003	0.003	1.000
2	0.011	0.014	0.997
3	0.029	0.042	0.986
4	0.057	0.100	0.958
5	0.092	0.191	0.900
6	0.122	0.313	0.809

X	P(X)	C(X)	D(X)
7	0.140	0.453	0.687
8	0.140	0.593	0.547
9	0.124	0.717	0.407
10	0.099	0.816	0.283
11	0.072	0.888	0.184
12	0.048	0.936	0.112
13	0.030	0.966	0.064
14	0.017	0.983	0.034
15	0.009	0.992	0.017
16	0.005	0.996	0.008
17	0.002	0.998	0.004
18	0.001	0.999	0.002
19	0.000	1.000	0.001

U= 8.50

X	P(X)	C(X)	D(X)
1	0.002	0.002	1.000
2	0.007	0.009	0.998
3	0.021	0.030	0.991
4	0.044	0.074	0.970
5	0.075	0.150	0.926
6	0.107	0.256	0.850
7	0.129	0.386	0.744
8	0.138	0.523	0.614
9	0.130	0.653	0.477
10	0.110	0.763	0.347
11	0.085	0.849	0.237
12	0.060	0.909	0.151
13	0.040	0.949	0.091
14	0.024	0.973	0.051
15	0.014	0.986	0.027
16	0.007	0.993	0.014
17	0.004	0.997	0.007
18	0.002	0.999	0.003
19	0.001	0.999	0.001
20	0.000	1.000	0.001

U= 9.00

X	P(X)	C(X)	D(X)
1	0.001	0.001	1.000
2	0.005	0.006	0.999
3	0.015	0.021	0.994
4	0.034	0.055	0.979
5	0.061	0.116	0.945
6	0.091	0.207	0.884
7	0.117	0.324	0.793
8	0.132	0.456	0.676
9	0.132	0.587	0.544
10	0.119	0.706	0.413
11	0.097	0.803	0.294
12	0.073	0.876	0.197
13	0.050	0.926	0.124
14	0.032	0.959	0.074
15	0.019	0.978	0.041
16	0.011	0.989	0.022
17	0.006	0.995	0.011
18	0.003	0.998	0.005
19	0.001	0.999	0.002
20	0.001	1.000	0.001

U= 9.50

X	P(X)	C(X)	D(X)
1	0.001	0.001	1.000
2	0.003	0.004	0.999
3	0.011	0.015	0.996
4	0.025	0.040	0.985
5	0.048	0.089	0.960
6	0.076	0.165	0.911
7	0.104	0.269	0.835
8	0.123	0.392	0.731
9	0.130	0.522	0.608
10	0.124	0.645	0.478
11	0.107	0.752	0.355
12	0.084	0.836	0.248
13	0.062	0.898	0.164
14	0.042	0.940	0.102
15	0.027	0.967	0.060
16	0.016	0.982	0.033

X	P(X)	C(X)	D(X)
17	0.009	0.991	0.018
18	0.005	0.996	0.009
19	0.002	0.998	0.004
20	0.001	0.999	0.002
21	0.000	1.000	0.001

U= 10.00

X	P(X)	C(X)	D(X)
2	0.002	0.003	1.000
3	0.008	0.010	0.997
4	0.019	0.029	0.990
5	0.038	0.067	0.971
6	0.063	0.130	0.933
7	0.090	0.220	0.870
8	0.113	0.333	0.780
9	0.125	0.458	0.667
10	0.125	0.583	0.542
11	0.114	0.697	0.417
12	0.095	0.792	0.303
13	0.073	0.864	0.208
14	0.052	0.917	0.136
15	0.035	0.951	0.083
16	0.022	0.973	0.049
17	0.013	0.986	0.027
18	0.007	0.993	0.014
19	0.004	0.997	0.007
20	0.002	0.998	0.003
21	0.001	0.999	0.002
22	0.000	1.000	0.001

U= 10.50

X	P(X)	C(X)	D(X)
2	0.002	0.002	1.000
3	0.005	0.007	0.998
4	0.014	0.021	0.993
5	0.029	0.050	0.979

X	P(X)	C(X)	D(X)
6	0.051	0.102	0.950
7	0.077	0.179	0.898
8	0.101	0.279	0.821
9	0.118	0.397	0.721
10	0.124	0.521	0.603
11	0.118	0.639	0.479
12	0.103	0.742	0.361
13	0.083	0.825	0.258
14	0.063	0.888	0.175
15	0.044	0.932	0.112
16	0.029	0.960	0.068
17	0.018	0.978	0.040
18	0.010	0.988	0.022
19	0.006	0.994	0.012
20	0.003	0.997	0.006
21	0.002	0.999	0.003
22	0.001	0.999	0.001
23	0.000	1.000	0.001

U= 11.00

X	P(X)	C(X)	D(X)
2	0.001	0.001	1.000
3	0.004	0.005	0.999
4	0.010	0.015	0.995
5	0.022	0.038	0.985
6	0.041	0.079	0.962
7	0.065	0.143	0.921
8	0.089	0.232	0.857
9	0.109	0.341	0.768
10	0.119	0.460	0.659
11	0.119	0.579	0.540
12	0.109	0.689	0.421
13	0.093	0.781	0.311
14	0.073	0.854	0.219
15	0.053	0.907	0.146
16	0.037	0.944	0.093
17	0.024	0.968	0.056
18	0.015	0.982	0.032
19	0.008	0.991	0.018
20	0.005	0.995	0.009
21	0.002	0.998	0.005
22	0.001	0.999	0.002

X	P(X)	C(X)	D(X)
23	0.001	1.000	0.001

U= 11.50

X	P(X)	C(X)	D(X)
2	0.001	0.001	1.000
3	0.003	0.003	0.999
4	0.007	0.011	0.997
5	0.017	0.028	0.989
6	0.033	0.060	0.972
7	0.053	0.114	0.940
8	0.077	0.191	0.886
9	0.098	0.289	0.809
10	0.113	0.402	0.711
11	0.118	0.520	0.598
12	0.113	0.633	0.480
13	0.100	0.733	0.367
14	0.082	0.815	0.267
15	0.063	0.878	0.185
16	0.045	0.924	0.122
17	0.031	0.954	0.076
18	0.020	0.974	0.046
19	0.012	0.986	0.026
20	0.007	0.992	0.014
21	0.004	0.996	0.008
22	0.002	0.998	0.004
23	0.001	0.999	0.002
24	0.000	1.000	0.001

U= 12.00

X	P(X)	C(X)	D(X)
3	0.002	0.002	0.999
4	0.005	0.008	0.998
5	0.013	0.020	0.992
6	0.025	0.046	0.980
7	0.044	0.090	0.954
8	0.066	0.155	0.910

X	P(X)	C(X)	D(X)
9	0.087	0.242	0.845
10	0.105	0.347	0.758
11	0.114	0.462	0.653
12	0.114	0.576	0.538
13	0.106	0.682	0.424
14	0.090	0.772	0.318
15	0.072	0.844	0.228
16	0.054	0.899	0.156
17	0.038	0.937	0.101
18	0.026	0.963	0.063
19	0.016	0.979	0.037
20	0.010	0.988	0.021
21	0.006	0.994	0.012
22	0.003	0.997	0.006
23	0.002	0.999	0.003
24	0.001	0.999	0.001
25	0.000	1.000	0.001

U= 12.50

X	P(X)	C(X)	D(X)
3	0.001	0.002	1.000
4	0.004	0.005	0.998
5	0.009	0.015	0.995
6	0.020	0.035	0.985
7	0.035	0.070	0.965
8	0.055	0.125	0.930
9	0.077	0.201	0.875
10	0.096	0.297	0.799
11	0.109	0.406	0.703
12	0.113	0.519	0.594
13	0.109	0.628	0.481
14	0.097	0.725	0.372
15	0.081	0.806	0.275
16	0.063	0.869	0.194
17	0.047	0.916	0.131
18	0.032	0.948	0.084
19	0.021	0.969	0.052
20	0.013	0.983	0.031
21	0.008	0.991	0.017
22	0.004	0.995	0.009
23	0.002	0.998	0.005
24	0.001	0.999	0.002

X	P(X)	C(X)	D(X)
25	0.001	0.999	0.001
26	0.000	1.000	0.001

U= 13.00

X	P(X)	C(X)	D(X)
3	0.001	0.001	1.000
4	0.003	0.004	0.999
5	0.007	0.011	0.996
6	0.015	0.026	0.989
7	0.028	0.054	0.974
8	0.046	0.100	0.946
9	0.066	0.166	0.900
10	0.086	0.252	0.834
11	0.101	0.353	0.748
12	0.110	0.463	0.647
13	0.110	0.573	0.537
14	0.102	0.675	0.427
15	0.088	0.764	0.325
16	0.072	0.835	0.236
17	0.055	0.890	0.165
18	0.040	0.930	0.110
19	0.027	0.957	0.070
20	0.018	0.975	0.043
21	0.011	0.986	0.025
22	0.006	0.992	0.014
23	0.004	0.996	0.008
24	0.002	0.998	0.004
25	0.001	0.999	0.002
26	0.001	1.000	0.001

U= 13.50

X	P(X)	C(X)	D(X)
3	0.001	0.001	1.000
4	0.002	0.003	0.999
5	0.005	0.008	0.997
6	0.012	0.019	0.992

X	P(X)	C(X)	D(X)
7	0.022	0.041	0.981
8	0.038	0.079	0.959
9	0.056	0.135	0.921
10	0.076	0.211	0.865
11	0.093	0.304	0.789
12	0.105	0.409	0.696
13	0.109	0.518	0.591
14	0.105	0.623	0.482
15	0.095	0.718	0.377
16	0.080	0.798	0.282
17	0.063	0.861	0.202
18	0.047	0.908	0.139
19	0.034	0.942	0.092
20	0.023	0.965	0.058
21	0.015	0.980	0.035
22	0.009	0.989	0.020
23	0.005	0.994	0.011
24	0.003	0.997	0.006
25	0.002	0.998	0.003
26	0.001	0.999	0.002
27	0.000	1.000	0.001

U= 14.00

X	P(X)	C(X)	D(X)
4	0.001	0.002	1.000
5	0.004	0.006	0.998
6	0.009	0.014	0.994
7	0.017	0.032	0.986
8	0.030	0.062	0.968
9	0.047	0.109	0.938
10	0.066	0.176	0.891
11	0.084	0.260	0.824
12	0.098	0.358	0.740
13	0.106	0.464	0.642
14	0.106	0.570	0.536
15	0.099	0.669	0.430
16	0.087	0.756	0.331
17	0.071	0.827	0.244
18	0.055	0.883	0.173
19	0.041	0.923	0.117
20	0.029	0.952	0.077
21	0.019	0.971	0.048

X	P(X)	C(X)	D(X)
22	0.012	0.983	0.029
23	0.007	0.991	0.017
24	0.004	0.995	0.009
25	0.002	0.997	0.005
26	0.001	0.999	0.003
27	0.001	0.999	0.001
28	0.000	1.000	0.001

U= 14.50

X	P(X)	C(X)	D(X)
4	0.001	0.001	1.000
5	0.003	0.004	0.999
6	0.007	0.010	0.996
7	0.013	0.024	0.990
8	0.024	[illegible]	0.976
9	0.039	0.088	0.952
10	0.057	0.145	0.912
11	0.075	0.220	0.855
12	0.091	0.311	0.780
13	0.101	0.413	0.689
14	0.105	0.518	0.587
15	0.102	0.619	0.482
16	0.092	0.711	0.381
17	0.079	0.790	0.289
18	0.063	0.853	0.210
19	0.048	0.901	0.147
20	0.035	0.936	0.099
21	0.024	[illegible]	0.064
22	0.016	[illegible]	0.040
23	0.010	0.986	0.024
24	0.006	0.992	0.014
25	0.004	0.996	0.008
26	0.002	0.998	0.004
27	0.001	0.999	0.002
28	0.001	0.999	0.001
29	0.000	1.000	0.001

U= 15.00

X	P(X)	C(X)	D(X)
4	0.001	0.001	1.000
5	0.002	0.003	0.999
6	0.005	0.008	0.997
7	0.010	0.018	0.992
8	0.019	0.037	0.982
9	0.032	0.070	0.963
10	0.049	0.118	0.930
11	0.066	0.185	0.882
12	0.083	0.268	0.815
13	0.096	0.363	0.732
14	0.102	0.466	0.637
15	0.102	0.568	0.534
16	0.096	0.664	0.432
17	0.085	0.749	0.336
18	0.071	0.819	0.251
19	0.056	0.875	0.181
20	0.042	0.917	0.125
21	0.030	0.947	0.083
22	0.020	0.967	0.053
23	0.013	0.981	0.033
24	0.008	0.989	0.019
25	0.005	0.994	0.011
26	0.003	0.997	0.006
27	0.002	0.998	0.003
28	0.001	0.999	0.002
29	0.000	1.000	0.001

U= 15.50

X	P(X)	C(X)	D(X)
5	0.001	0.002	0.999
6	0.004	0.006	0.998
7	0.008	0.013	0.994
8	0.015	0.029	0.987
9	0.026	0.055	0.971
10	0.041	0.096	0.945
11	0.058	0.154	0.904
12	0.074	0.228	0.846
13	0.089	0.317	0.772
14	0.098	0.415	0.683

X	P(X)	C(X)	D(X)
15	0.102	0.517	0.585
16	0.098	0.615	0.483
17	0.090	0.705	0.385
18	0.077	0.782	0.295
19	0.063	0.846	0.218
20	0.049	0.894	0.154
21	0.036	0.930	0.106
22	0.025	0.956	0.070
23	0.017	0.973	0.044
24	0.011	0.984	0.027
25	0.007	0.991	0.016
26	0.004	0.995	0.009
27	0.002	0.997	0.005
28	0.001	0.999	0.003
29	0.001	0.999	0.001
30	0.000	1.000	0.001

U= 16.00

X	P(X)	C(X)	D(X)
5	0.001	0.001	1.000
6	0.003	0.004	0.999
7	0.006	0.010	0.996
8	0.012	0.022	0.990
9	0.021	0.043	0.978
10	0.034	0.077	0.957
11	0.050	0.127	0.923
12	0.066	0.193	0.873
13	0.081	0.275	0.807
14	0.093	0.368	0.725
15	0.099	0.467	0.632
16	0.099	0.566	0.533
17	0.093	0.659	0.434
18	0.083	0.742	0.341
19	0.070	0.812	0.258
20	0.056	0.868	0.188
21	0.043	0.911	0.132
22	0.031	0.942	0.089
23	0.022	0.963	0.058
24	0.014	0.978	0.037
25	0.009	0.987	0.022
26	0.006	0.993	0.013
27	0.003	0.996	0.007

X	P(X)	C(X)	D(X)
28	0.002	0.998	0.004
29	0.001	0.999	0.002
30	0.001	0.999	0.001
31	0.000	1.000	0.001

U= 16.50

X	P(X)	C(X)	D(X)
5	0.001	0.001	1.000
6	0.002	0.003	0.999
7	0.005	0.007	0.997
8	0.009	0.017	0.993
9	0.017	0.034	0.983
10	0.028	0.062	0.966
11	0.042	0.104	0.938
12	0.058	0.162	0.896
13	0.074	0.236	0.838
14	0.087	0.323	0.764
15	0.095	0.418	0.677
16	0.098	0.516	0.582
17	0.096	0.612	0.484
18	0.088	0.700	0.388
19	0.076	0.776	0.300
20	0.063	0.838	0.224
21	0.049	0.888	0.162
22	0.037	0.925	0.112
23	0.027	0.951	0.075
24	0.018	0.970	0.049
25	0.012	0.982	0.030
26	0.008	0.989	0.018
27	0.005	0.994	0.011
28	0.003	0.997	0.006
29	0.002	0.998	0.003
30	0.001	0.999	0.002
31	0.000	1.000	0.001

U= 17.00

X	P(X)	C(X)	D(X)
6	0.001	0.002	0.999
7	0.003	0.005	0.998
8	0.007	0.013	0.995
9	0.014	0.026	0.987
10	0.023	0.049	0.974
11	0.036	0.085	0.951
12	0.050	0.135	0.915
13	0.066	0.201	0.865
14	0.080	0.281	0.799
15	0.091	0.371	0.719
16	0.096	0.468	0.629
17	0.096	0.564	0.532
18	0.091	0.655	0.436
19	0.081	0.736	0.345
20	0.069	0.805	0.264
21	0.056	0.861	0.195
22	0.043	0.905	0.139
23	0.032	0.937	0.095
24	0.023	0.959	0.063
25	0.015	0.975	0.041
26	0.010	0.985	0.025
27	0.006	0.991	0.015
28	0.004	0.995	0.009
29	0.002	0.997	0.005
30	0.001	0.999	0.003
31	0.001	0.999	0.001
32	0.000	1.000	0.001

U= 17.50

X	P(X)	C(X)	D(X)
6	0.001	0.001	1.000
7	0.003	0.004	0.999
8	0.005	0.009	0.996
9	0.011	0.020	0.991
10	0.019	0.039	0.980
11	0.030	0.068	0.961
12	0.043	0.112	0.932
13	0.058	0.170	0.888
14	0.073	0.243	0.830

X	P(X)	C(X)	D(X)
15	0.085	0.328	0.757
16	0.093	0.420	0.672
17	0.096	0.516	0.580
18	0.093	0.609	0.484
19	0.086	0.695	0.391
20	0.075	0.769	0.305
21	0.062	0.832	0.231
22	0.050	0.882	0.168
23	0.038	0.919	0.118
24	0.028	0.947	0.081
25	0.019	0.966	0.053
26	0.013	0.979	0.034
27	0.008	0.987	0.021
28	0.005	0.993	0.013
29	0.003	0.996	0.007
30	0.002	0.998	0.004
31	0.001	0.999	0.002
32	0.001	0.999	0.001
33	0.000	1.000	0.001

U= 18.00

X	P(X)	C(X)	D(X)
6	0.001	0.001	1.000
7	0.002	0.003	0.999
8	0.004	0.007	0.997
9	0.008	0.015	0.993
10	0.015	0.030	0.985
11	0.025	0.055	0.970
12	0.037	0.092	0.945
13	0.051	0.143	0.908
14	0.065	0.208	0.857
15	0.079	0.287	0.792
16	0.088	0.375	0.713
17	0.094	0.469	0.625
18	0.094	0.562	0.531
19	0.089	0.651	0.438
20	0.080	0.731	0.349
21	0.068	0.799	0.269
22	0.056	0.855	0.201
23	0.044	0.899	0.145
24	0.033	0.932	0.101
25	0.024	0.955	0.068

X	P(X)	C(X)	D(X)
26	0.016	0.972	0.045
27	0.011	0.983	0.028
28	0.007	0.990	0.017
29	0.004	0.994	0.010
30	0.003	0.997	0.006
31	0.002	0.998	0.003
32	0.001	0.999	0.002
33	0.000	1.000	0.001

U= 18.50

X	P(X)	C(X)	D(X)
6	0.001	0.001	1.000
7	0.001	0.002	0.999
8	0.003	0.005	0.998
9	0.006	0.012	0.995
10	0.012	0.024	0.988
11	0.020	0.044	0.976
12	0.031	0.075	0.956
13	0.044	0.119	0.925
14	0.058	0.177	0.881
15	0.072	0.249	0.823
16	0.083	0.332	0.751
17	0.090	0.423	0.668
18	0.093	0.516	0.577
19	0.091	0.606	0.484
20	0.084	0.690	0.394
21	0.074	0.764	0.310
22	0.062	0.826	0.236
23	0.050	0.875	0.174
24	0.038	0.914	0.125
25	0.028	0.942	0.086
26	0.020	0.963	0.058
27	0.014	0.977	0.037
28	0.009	0.986	0.023
29	0.006	0.992	0.014
30	0.004	0.995	0.008
31	0.002	0.997	0.005
32	0.001	0.999	0.003
33	0.001	0.999	0.001
34	0.000	1.000	0.001

U= 19.00

X	P(X)	C(X)	D(X)
7	0.001	0.002	0.999
8	0.002	0.004	0.998
9	0.005	0.009	0.996
10	0.009	0.018	0.991
11	0.016	0.035	0.982
12	0.026	0.061	0.965
13	0.038	0.098	0.939
14	0.051	0.150	0.902
15	0.065	0.215	0.850
16	0.077	0.292	0.785
17	0.086	0.378	0.708
18	0.091	0.469	0.622
19	0.091	0.561	0.531
20	0.087	0.647	0.439
21	0.078	0.725	0.353
22	0.068	0.793	0.275
23	0.056	0.849	0.207
24	0.044	0.893	0.151
25	0.034	0.927	0.107
26	0.025	0.951	0.073
27	0.017	0.969	0.049
28	0.012	0.980	0.031
29	0.008	0.988	0.020
30	0.005	0.993	0.012
31	0.003	0.996	0.007
32	0.002	0.998	0.004
33	0.001	0.999	0.002
34	0.001	0.999	0.001
35	0.000	1.000	0.001

U= 19.50

X	P(X)	C(X)	D(X)
7	0.001	0.001	1.000
8	0.002	0.003	0.999
9	0.004	0.007	0.997
10	0.007	0.014	0.993
11	0.013	0.027	0.986
12	0.021	0.049	0.973
13	0.032	0.081	0.951

X	P(X)	C(X)	D(X)
14	0.045	0.126	0.919
15	0.058	0.184	0.874
16	0.071	0.255	0.816
17	0.081	0.336	0.745
18	0.088	0.425	0.664
19	0.091	0.515	0.575
20	0.088	0.603	0.485
21	0.082	0.685	0.397
22	0.073	0.758	0.315
23	0.062	0.820	0.242
24	0.050	0.870	0.180
25	0.039	0.909	0.130
26	0.029	0.938	0.091
27	0.021	0.959	0.062
28	0.015	0.974	0.041
29	0.010	0.984	0.026
30	0.006	0.990	0.016
31	0.004	0.994	0.010
32	0.002	0.997	0.006
33	0.001	0.998	0.003
34	0.001	0.999	0.002
35	0.000	0.999	0.001
36	0.000	1.000	0.001

U= 20.00

X	P(X)	C(X)	D(X)
7	0.001	0.001	1.000
8	0.001	0.002	0.999
9	0.003	0.005	0.998
10	0.006	0.011	0.995
11	0.011	0.021	0.989
12	0.018	0.039	0.979
13	0.027	0.066	0.961
14	0.039	0.105	0.934
15	0.052	0.157	0.895
16	0.065	0.221	0.843
17	0.076	0.297	0.779
18	0.084	0.381	0.703
19	0.089	0.470	0.619
20	0.089	0.559	0.530
21	0.085	0.644	0.441
22	0.077	0.721	0.356

X	P(X)	C(X)	D(X)
23	0.067	0.787	0.279
24	0.056	0.843	0.213
25	0.045	0.888	0.157
26	0.034	0.922	0.112
27	0.025	0.948	0.078
28	0.018	0.966	0.052
29	0.013	0.978	0.034
30	0.008	0.987	0.022
31	0.005	0.992	0.013
32	0.003	0.995	0.008
33	0.002	0.997	0.005
34	0.001	0.999	0.003
35	0.001	0.999	0.001
36	0.000	1.000	0.001

U= 20.50

X	P(X)	C(X)	D(X)
8	0.001	0.002	0.999
9	0.002	0.004	0.998
10	0.005	0.008	0.996
11	0.008	0.017	0.992
12	0.014	0.031	0.983
13	0.023	0.054	0.969
14	0.033	0.087	0.946
15	0.045	0.132	0.913
16	0.058	0.190	0.868
17	0.070	0.261	0.810
18	0.080	0.340	0.739
19	0.086	0.426	0.660
20	0.088	0.515	0.574
21	0.086	0.601	0.485
22	0.080	0.681	0.399
23	0.072	0.753	0.319
24	0.061	0.814	0.247
25	0.050	0.864	0.186
26	0.040	0.904	0.136
27	0.030	0.934	0.096
28	0.022	0.956	0.066
29	0.016	0.971	0.044
30	0.011	0.982	0.029
31	0.007	0.989	0.018
32	0.004	0.993	0.011

X	P(X)	C(X)	D(X)
33	0.003	0.996	0.007
34	0.002	0.998	0.004
35	0.001	0.999	0.002
36	0.001	0.999	0.001
37	0.000	1.000	0.001

U= 21.00

X	P(X)	C(X)	D(X)
8	0.001	0.001	1.000
9	0.002	0.003	0.999
10	0.003	0.006	0.997
11	0.007	0.013	0.994
12	0.012	0.025	0.987
13	0.019	0.043	0.975
14	0.028	0.072	0.957
15	0.040	0.111	0.928
16	0.052	0.163	0.889
17	0.064	0.227	0.837
18	0.075	0.302	0.773
19	0.083	0.384	0.698
20	0.087	0.471	0.616
21	0.087	0.558	0.529
22	0.083	0.640	0.442
23	0.076	0.716	0.360
24	0.066	0.782	0.284
25	0.056	0.838	0.218
26	0.045	0.883	0.162
27	0.035	0.917	0.117
28	0.026	0.944	0.083
29	0.019	0.963	0.056
30	0.013	0.976	0.037
31	0.009	0.985	0.024
32	0.006	0.991	0.015
33	0.004	0.994	0.009
34	0.002	0.997	0.006
35	0.001	0.998	0.003
36	0.001	0.999	0.002
37	0.000	0.999	0.001
38	0.000	1.000	0.001

U= 21.50

X	P(X)	C(X)	D(X)
8	0.001	0.001	1.000
9	0.001	0.002	0.999
10	0.003	0.005	0.998
11	0.005	0.010	0.995
12	0.009	0.019	0.990
13	0.015	0.035	0.981
14	0.024	0.059	0.965
15	0.034	0.093	0.941
16	0.046	0.139	0.907
17	0.058	0.196	0.861
18	0.069	0.266	0.804
19	0.078	0.344	0.734
20	0.084	0.428	0.656
21	0.086	0.514	0.572
22	0.084	0.599	0.486
23	0.079	0.677	0.401
24	0.071	0.748	0.323
25	0.061	0.809	0.252
26	0.050	0.859	0.191
27	0.040	0.899	0.141
28	0.031	0.929	0.101
29	0.023	0.952	0.071
30	0.016	0.968	0.048
31	0.011	0.980	0.032
32	0.008	0.987	0.020
33	0.005	0.992	0.013
34	0.003	0.995	0.008
35	0.002	0.997	0.005
36	0.001	0.999	0.003
37	0.001	0.999	0.001
38	0.000	1.000	0.001

SECTION VII

MONITORING OF CONTRACTORS RELIABILITY AND MAINTAINABILITY PROGRAMS

SECTION VII

MONITORING OF CONTRACTORS RELIABILITY AND MAINTAINABILITY PROGRAMS

FOREWORD

The purpose of this section is to provide guidance to the System Program Offices (SPO) Reliability and Maintainability (R/M) Monitors in organization and operation of an R/M program on their contracts.

The duties of the Monitor are outlined in AFSCR 80-1 and ESDR 80-2. However, specific instructions, or an operating manual are not presently available in any other AF publication. This section partially fills the need by outlining steps to be taken, and points to be checked as the work progresses. When used in conjunction with USAF Specification Bulletin 506 it considers R/M throughout the AF cycle, from definition through acquisition phases.

Achievement of ESD reliability objectives requires that the Specification and Statement of Work (SOW) be explicit in what a contractor is required to do, but no amount of legal phraseology can produce the results of a good reliability engineering program, actively pursued.

SECTION VII

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APPENDIX

MONITORING OF CONTRACTORS
RELIABILITY AND MAINTAINABILITY
PROGRAMS

1. Introduction:

a. Explanation of Terms:[1]

(1) Reliability. The probability that a given system/equipment will perform its intended function, without failure, for a specified period of time, when operated in its prescribed manner.

(2) Maintainability (Operational). The probability that when a maintenance action is initiated under stated conditions a failed system/equipment will be restored to operable condition within a specified total downtime.

b. Impact of R/M on Overall Program. The reliability and maintainability inherent in any given system affects the overall system operation. These effects include the quantity of spares which must be provisioned to support it, the amount of maintenance which will be required to achieve a given degree of operational readiness, and the number of systems required to do a particular job, i.e., target coverage, continuous satellite relay capability, continuous operation for a given period, etc. These R/M parameters also determine the number of systems required to accomplish a given set of objectives, the magnitude of development funds required, the skills and facilities required for development and production, and the amount of time required to evolve from the definition to the operational phase.

c. R/M Requirements. For a given system or equipment, requirements are based upon the Specific Operational Requirements (SOR). The SORs are established by USAF after study of AF defense requirements. Usually trade-offs are necessary to fit the requirements within budget or time limitations. These may involve Reliability versus Maintainability to achieve a certain overall Availability (A); Reliability versus Cost; Reliability versus Schedule; Reliability versus Performance, etc. Once the R/M requirements have been established it is imperative that they be achieved since they have a direct impact on every major element of the program.

[1] For additional terms pertaining to R/M matters see MIL-STD-721 and MIL-STD-829.

d. Approach. The R/M requirements will be achieved only by good planning and vigorous management. To achieve these objectives the SPO must define the program in terms of detailed R/M requirements.

To monitor progress on the contract and ultimate achievement of the requirements necessitates development of an R/M Program Plan[1] with specific tasks and interim objectives, which can be audited on a time-phased basis to determine accomplishments.

e. R/M Functions. The list of functions or activities which should be performed during system development and acquisition can be expanded almost without bound. A typical list of key functions for which an input on reliability and maintainability is required, and which may involve direct contributions by an R/M Monitor, is summarized below. By expanding upon this basic framework a Monitor can develop a full R/M program. These functions have been abbreviated and grouped according to the various phases of system development.

MAJOR EVENT	RELIABILITY/MAINTAINABILITY PARTICIPATION
Conceptual Phase	
Feasibility Study	Identify achievable R/M. Identify potential problems. Outline approach required.
Publish SOR	Provide R/M quantitative requirements or objectives for inclusion in SOR.
Definition Phase	
Prepare Work Statements	Provide program requirements and tasks.
Select source	Evaluate bidders proposals.
Initiate work	Brief contractors on approach, policy, etc.
Conduct trade-offs	Provide data and technical direction/evaluation.
Establish base line	Provide analysis and final requirements.

[1]Program plans have been covered in ESDP 80-2.

MAJOR EVENT	RELIABILITY/MAINTAINABILITY PARTICIPATION
Define program	Establish program elements, applicable documents, and approved program plans.
Acquisition Phase	
Let contracts	Provide work statements.
Begin design	Provide analysis. Control parts selection. Approve subcontractors. Design tests.
Finalize design	Provide design reviews. Approve specifications, drawings, etc.
Conduct testing,	Provide test requirements. Design tests. Interpret data.
Evaluate results	Identify discrepancies. Establish corrective action. Retest as necessary.
Manufacture	Coordinate all process controls, tests, and inspections with Quality Control.
Shipping and storage	Evaluate procedures and controls.
Installation and checkout	Monitor progress, problems, and corrective actions. Phase operations data into basic data system.
Operational Phase	
Activate	Transition from acquisition data to operational data for measurement and control of reliability and maintainability.
	Verify any updating programs.
	Activate and support in-service engineering functions.

f. R/M Monitor's Function:

(1) The R/M Monitor's primary responsibility is to serve as the SPO focal point for R/M activities. The complete responsibilities are clearly delineated in ESDR 80-2 and ESDR 80-4. They encompass work within the SPO, the supporting activities, and direct monitoring of the contractor and subcontractors.

(2) The SPO Monitor does not replace the contractor's R/M organization but serves to supplement, analyze, and control the contractor's work. The need for the AF Monitor's position is based on the fact that contractors are of necessity profit oriented while the AF must be mission oriented.

(3) The Monitor serves a vital role in achievement of the overall system/equipments requirements. While AF, AFSC, and ESD regulations define the Monitor's responsibilities, AF publications do not cover instructions on development and operation of an R/M program. While this pamphlet is not all encompassing it does cover the important steps in operating a program, and points out some problem areas for particular attention in monitoring. These items are based on experience on other R/M programs and will assist the monitors in getting their programs into operation smoothly and quickly.

2. Preparation for Monitoring:

a. Precontract:

(1) The Monitor should review the specifications and SOW, and develop a monitoring plan based on the tasks described. If the SPO is specific and detailed in the precontract stage, the easier will be the work in the later stages. Detail what is to be covered. Note that some items in R/M are deliverable; i.e., plans or reports, others are requirements which will require checking in-plant. Determine which items may require a visit to the contractor's plant and which items can be reviewed at ESD[1]. The important point, is to develop a check list of what is expected from the contractor. The Monitor should be prepared at the Bidders' Briefing to outline what is required.

(2) One of the basic monitoring problems, assuming that the contract and specification are adequate, is that contracts and specifications, with few exceptions, establish a requirement which is based on end-item test (e.g., 1000 hours mean time between failures (MTBF) or 99.99% availability) of the final product but do not provide any interim check points. This means that the contractor can start design and continue on through production, to final test before the SPO is aware that R/M requirements will not be met. This may result in a situation where delivery will become of paramount importance and the Government is forced to accept substandard items or face a long delay to reprocure the equipment. Most contracts allow progress

[1]A new procedure covering the use of DOD Form 1423, Contractor Data Requirements List, is being prepared at ESD. It will be incorporated into the contracts and spell out all deliverable data type items.

payments. If these payments are controlled in an adequate manner, the Monitor can do much to assure attainment of AF goals. One of the legal means for controlling this is to set intermediate requirements and monitor the work as it progresses.

(3) It should be noted that there are two general types of specifications:

(a) A "performance type" specification in which the contractor is given the problem and the end result desired. Within certain limitations, standard parts, etc., the contractor works toward the goal.

(b) An "equipment type" specification, in which the contractor is told what to use, "off-the-shelf" Government Furnished Equipment (GFE), etc., and there is less chance for "a state-of-the-art" breakthrough.

Request for Proposal (RFP) statements to the bidders must be specific as to what is expected of them. The work involved on these types of contracts differs. When the contractor is developing new designs and approaches, the emphasis is placed in the design stage. Where the contractor is directed to use existing equipments the emphasis shifts to determining the equipments to be used, what weak points have been previously noted, and how the system should be configured.

(4) Initially, the Monitor should set up his own listings of major programs (systems and subsystems). Identify who in the SPO is assigned responsibility as Project Engineer, Production Specialist, Buyer, RADC Support, RADC Engineer, etc. In each case list the telephone number, position title, and organization. A list of specifications applicable, R/M intermediate and final goals, SPO estimates of time-phasing, manloading, and task duration, should also be estimated.

b. First Post Contract Award Meeting:

(1) At this point, after award of contract, the Monitor can give a more specific briefing to contractor. The Air Force Procurement Instructions (AFPIs) require, on larger contracts, that these briefings be held within 30 days of contract award. If not scheduled by the contracting officer the Monitor should request that the contractor's R/M group meet with the SPO R/M representatives. At this meeting the Monitor can give direction and clarification of specific tasks if required.

(2) Request the contractors R/M Plan be submitted as early as possible so it can be reviewed. Determine if contractor understands all R/M aspects required in the contract, and if his general approach and understanding follows the Monitor's planned check list.

(3) It is possible that some problems may arise at the meeting that cannot be resolved at that time. The problem should be discussed and defined. Then specific assignment should be made to a person or activity; e.g., contractors design group or SPO contracting office, to follow the matter through. In addition to assigning the problem for resolution, a date for reporting on the progress or resolution should be established. These problems and assignments should be incorporated into the minutes of meeting as a method of checking progress.

(4) Establish the working arrangements and contact to be used in development and operation of the program. The contractor should be given an organization chart of the SPO, with personnel assigned to various functions, and he should be requested to provide similar information to the SPO.

(5) The Monitor should establish certain policies with respect to all meetings with the contractor. As a minimum these should include:

(a) That an agenda be prepared and distributed in advance of each meeting.

(b) That minutes of each meeting be kept, and be distributed to all parties concerned.

(c) That problems pending or resolved be included in the minutes (see (3) above).

(d) That attendance at the meetings be kept as small as possible, consistent with the work to be covered.

(e) That regular meetings be held with contractor personnel to check progress made. A frequency of about four to six week intervals has been found to be practical. The meeting dates should be adjusted as needed to check contract mile posts.

c. Second Post Contract Award Meeting:

(1) Review contractor's R/M Plan in detail with his representatives. The discussion should cover the contractors plan on a task by task basis and assure that all contractual requirements have been met. If any points have not been covered in the plan, or if the statement of the work to be done is not clear, the plan or the contract should be amended. If this involves changes in price, delivery, etc., written approval of the contracting officer must be obtained.

(2) Attention should be paid to the time-phasing, manloading, and task duration elements of the plan. Comparison of the contractor's allocations should be made against the SPO Monitor's estimates. (NOTE: By establishing these items early in the contract, logical redirection of the program can be made later without incurring major overruns.)

(3) Obtain from the contractor a list of his major subcontractors, their schedules, the guidance documents used to control them, the reporting procedures used for in-house, and for external control. These documents should be approved by the SPO prior to implementation. Final approval of the contractor R/M Plan should be contingent on approval of these items.

(4) Agreement should be obtained on reporting periods, report format, and content. A simple but well documented engineering letter type report is desired. The emphasis should be on report content, not appearance. Depending on the program involved, scope and duration, it may be acceptable to have the R/M reports as part of the overall progress report rather than as separate reports.

(5) Get the R/M Math Model usually required in the program plan. This will serve as the base for checking progress on the contract. It should be updated and revised as the design and work progresses. (See Figure I.)

(6) Set up the specific monitoring points. (See Figure II, "Typical Growth Cycle".) Very few ESD contracts will fit this completely, but some points can be combined and the general trend should resemble this chart. Note particularly the curves and the Reliability values shown:

(a) Specified Reliability. This is the contractual requirement, shown as a constant value. This value is required as the end result on completion of the contract. In ESD contracts it represents the "operational" reliability required of the system/equipment.

(b) Predicted Reliability. This curve represents the contractor's predicted approach on a phased basis, to achievement of the specified reliability. In some cases, in the early stages of development, the predicted values may be below requirements. During this period the contractor should be expending engineering effort to improve the design to assure attainment of the goals. It should be noted this curve must ultimately <u>exceed</u> the requirements in order to assure achievement of the specified values. This is to allow for the inevitable degradation of the inherent reliability due to production, handling, etc. These interim predicted values should be obtained from the contractor and will allow for assessment of progress.

(c) Reliability Status. This curve represents the achieved results based on test or demonstration at the agreed on monitoring points. The results should equal or exceed the predicted values.

NOTE: These curves are the basic source of information for completion of the Reliability Status Report required by AFSCR 80-1.(RCS: AFSC-R44).

Not all contracts will follow these steps. In some cases equipment is GFE, "off-the-shelf", modified GFE, etc., but this chart can be modified as needed to allow for these variations and still give intermediate evaluation points. These Mile Posts should be used to REVIEW, MEASURE, REPORT, and CORRECT. Whenever the results do not appear to follow the predicted curves the monitor should take action. Do not wait until the contract has run so long that the SPO cannot consider termination or alternate approaches because of lack of time.

d. Elements of the Reliability Program Plan. Depending on the SOW tasks and the specifications referenced, the contractor is required to perform many of the following functions in his R/M program. The list is not complete and the depth that each item will have is dependent on the SOW.

(1) Develop R/M Plan.

(2) Develop and update the math model.

(3) Conduct critical item studies.

(4) Conduct special studies.

(5) Develop and implement a plan for control of subcontractors.

(6) Perform human factors analysis.

(7) Develop manufacturing and handling control procedures.

(8) Plan for and conduct training and indoctrination of personnel.

(9) Establish and operate a closed loop data collection and analysis system.

(10) Plan for and conduct design reviews.

(11) Analyze and evaluate modifications and Engineering Change Proposals (ECPs).

(12) Provide for a corrective action system for all phases of contract including sites, if applicable.

(13) Develop a test plan.

(14) Provide for test and evaluation.

(15) Establish reporting procedures.

(16) Provide planning for AGE and spares considerations.

(17) Check manuals; operating, installation, and repair.

The R/M Monitor's function is to determine that the plan is adequate and is followed completely.

3. Monitoring Procedures:

a. Weak Link Procedures. Weak link studies may be one of the items required by the SOW under special studies. In developing the specific tasks for the SOW consideration should be given to requiring the contractor to list, in his regular or special reports, those "weak links" or limiting factor items that have been found as work on the contract progresses. These are a distinct consideration from those items that would prevent the contractor from meeting his contractual requirements. Where a contractor fails to meet the specified contractual requirements corrective action is required by the contractor. In the case of a "weak links" requirement the contractor will deliver the required reliability or maintainability but must point out the limiting factors found, and detail what could be obtained with a given amount of engineering effort and production time to improve the system/equipment. The monitor should study and evaluate these weak links and recommend a course of action to the SPO.

b. Failure Reporting and Corrective Action Loops:[1]

(1) The contractor should detail his failure reporting and corrective action loop as part of his overall R/M Plan. In many cases, these may be part of his Quality Control manual which is required under MIL-Q-9858. The essential ingredients of any system are:

(a) All failures or problems are reported and fully documented. The type of data and details may vary depending on the phase of the contract.

(b) Analysis and tabulation of the data.

(c) Actions taken based on the data available.

(d) Evaluation of the actions taken.

(2) Typical data flow and feedback loops in various parts of the system cycle are shown as Figure III.

[1]For additional information on R/M Data Collection and Evaluation System see ESDP 80-3.

(3) Various forms are used in collection of data. Each failure reported should contain sufficient information to enable the contractor and SPO to make a proper evaluation of the trouble. The essential information elements for R/M purposes are listed in MIL-R-27542 and MIL-M-26512. To get all these elements may require two or more forms. Due to the nature of ESD systems, where redundancy is common, provision must also be made to get the operating time of the equipment/systems. Since equipments are not always operating due to redundancy, Preventative Maintenance (PM) or Corrective Maintenance (CM) provision must be made to obtain true operating time as the work progresses. A typical form is shown in Figure IV which is used to record an individual failure, and Figure V which is an operating time log used to determine operating time on a given drawer or cabinet.

(4) Points to watch in data collection:

(a) By personal observation and contacts with contractor personnel determine if all failures are recorded. Log books can be checked against failure reports to determine if the information has been documented. By checking supply room issue or requisition slips an indication of equipment failures and parts replacement can be obtained for cross checking purposes.

(b) Quality of entries is very important. For simplicity and ease of operation, most contractor data systems use coded entries. In checking entries the accuracy of coding is important. Equally important, however, is the determination of whether the failure is a primary or secondary failure, whether it was an engineering design problem or a production problem, etc. Contractual provision should be made, both on site and in the factory for the assistance of a qualified R/M engineer to work with operating and maintenance personnel in evaluation of the causes of failure.

(c) Cross checking of clock time versus elapsed time meters. Generally, command and control systems have one or more Elapsed Time Indicators (ETIs) per subsystem. For proper analysis, operating time must be kept on a discrete basis, such as a drawer or cabinet level. Periodic checks of clock time versus ETI time will give an indication of the accuracy of the records.

(d) Parts analyses records. Simple recording of parts failures, and replacement actions does not suffice for complete R/M work. Causes of repetitive failures or those which are critical to system operation, must be determined. To accomplish this may require a laboratory analysis of the failure. Figure VI is a sample form for use in following these items through the repair and return cycle. Note the detailed information required in completion of these forms. It is imperative that this information be complete and accurate if adequate performance is to be obtained.

(e) The fact that a record is made of the parts failure at the test site or proving ground, and that a copy of the form was sent to the prime or integration contractor is not proof that corrective action has been taken. When visiting the plant the monitor should check to determine the action taken and results obtained. This should be done by starting with the first office receiving the report and then following through, office by office, through recording, analysis, engineering, production, test, etc. Particular attention should be paid to those problems when failures are critical or repetitive.

(5) Use of AFM 66-1, Maintenance System Reporting. During FY 64 the AF will institute a Maintenance Data Collection System (MDCS) which is similar to the system outlined in AFM 66-1, presently the principle AF system for maintenance and logistic system reporting. A complete description of the system and instructions for its use will be contained in the revision of AFSCM 375-1 soon to be published. It is expected that this MDCS is to be instituted not later than the start of Category II testing (REF: AFR 80-14). To assure proper implementation of the MDCS, arrangements must be made for Work Unit Coding (WUC) early in the contract. Assignment of WUC is the responsibility of ROAMA.

c. <u>Engineering Change Proposals (ECPs), Non-ECPs, and Contract Modifications</u>. In most contracts for large equipments or systems which are pushing the "state-of-the-art", changes frequently become necessary. Depending on the type of change, and the time phasing, these may be ECP, non-ECP, etc. The definitions of these terms varies from contractor to contractor. The contractor should be required to analyze proposed changes for effect on R/M. The change request should state clearly:

(1) What is involved, the part, component, or equipment affected.

(2) Why change is proposed and reason for request.

(3) Number and location of equipments or systems involved.

(4) Cost per unit and total cost to effect the change.

(5) Effect on production/delivery schedules.

(6) Affect on R/M of the system/equipment.

(7) How the effect of the proposed change will be verified.

All statements should be clear and quantified; e.g., the MTBF is presently 100 hours. By changing the cut-out switch in the power supply to type XY which has a lower Failure Rate, 150 hours MTBF will be obtained. Example for form to used in reporting these proposed changes is shown as Figure VII and Figure VII-A. If the base line configuration has been established, the

R/M Monitor must assure that these proposed changes are processed through the SPO Configuration Control Board and that the R/M activity has a voice in the decision of the board.

d. Test and Demonstration Plans. General considerations of the test programs in Category testing are covered in AFR 80-14 and are further amplified in ESDP 375-2, A Typical Test Plan for Electronic Systems, a pamphlet which has been published by ESTT.

The R/M specifications require the contractor to develop test plans to demonstrate achievement of the required R/M characteristics to a given confidence level. It should be noted that Hq AFSC has directed that R/M shall be specified in all system contracts and that attainment shall be demonstrated prior to final payment.

Points for special attention in Test Programs:

(1) In establishing requirements consideration must be given to the degree of confidence and/or risk required since the cost of testing increases very sharply[1] when confidence limits in excess of 90% are specified.

(2) In complex redundant systems demonstration of overall system reliability may require lengthy test times. Careful analysis may allow for demonstrations on a subsystem or component basis that could be accepted. Careful check of system interface and switching needs should be made in determining the test approach.

(3) Contractor/SPO agreement on approach for accumulation of test time and repair time should be established. Ideally, the tests for R/M should be run independently of performance and other tests. Schedules frequently do not allow sufficient time for this. R/M Monitors should request ample time for running of R/M tests in accordance with applicable specifications, but all data accumulated during other tests should be used if possible. The data used must be properly evaluated. For example:

(a) If checking devices such as diagnostic routines or performance monitors are not available the maintenance time may be higher than normal.

(b) Checks must be made to determine that equipment is actually performing its function and not simply that the ETI is running

[1]For additional information on establishing test time requirements and risks see ESDP 80-5.

or that the power switch is "ON". Failures do occur which are not detected and this may give erroneous reliability values. Definite agreement must be reached, prior to start of test, on how the system is to be "exercised" and checked out.

(4) Due to the "concurrency concept" applicable on many ESD programs, shipment and installation of equipment sometimes occurs before testing or retrofit has been accomplished. Careful check should be made as to assignment of AF responsibilities and procedural details on the following:

(a) Conditional acceptance at plant.

(b) Engineering responsibility for data evaluation and/or design.

(c) Site engineering and installation acceptance.

(d) Retrofit acceptance and checkout.

(e) Final test and acceptance.

(5) Environmental test conditions should be specified in the test plan and should be in conformance with the original equipment/system specifications. On a system basis the environment control is sometimes limited. In equipment test, adequately controlled test chambers can usually be obtained. Care should be taken in specifying the conditions and in checking the controls. When original specifications do not cover this point agreement should be reached prior to start of the test. Consideration should be given to use of Advisory Group on Reliability of Electronic Equipment (AGREE) test conditions.

e. Agreement on Terms and Definitions. Prior to start of test, preferably as part of the basic R/M Plan, agreement should be reached on definition of terms, including modes of operation, equipment and systems failures, up-time ratios, mission success, etc. Basic references for these terms are found in MIL-STD-721, MIL-STD-829 and glossaries given in MIL-R-27542 and MIL-[illegible]512. Special consideration must be given to the degree of control the contractor has over the equipment and subsystems involved. If the contractor is not responsible for the intersite communications or for certain GFE used, the definitions must be adjusted to cover these items.

f. Critical Parts:

(1) Some items require special attention in program monitoring. These include:

(a) Items for which adequate R/M data is not available.

(b) Items having limited life due to natural ageing factors or degradation during test.

(c) Items requiring special handling during production, storage, or issue.

(2) All of the above should be specially documented and necessary planning and action taken to avoid system degradation. These plans and actions should be checked by the Monitor.

g. Control of Subcontractors. Standard Government procedure and civil contract law establishes relationship only between the customer (SPO) and the prime contractor. Contract stipulation is usually made that the prime contractor is responsible for his subcontractors' work, requiring that actions involving subcontractors should be directed through the prime contractor. Direct Government/subcontractor negotiations would require specific written authorization.

Prime contractors are expected to prepare instructions or technical operation procedures which supplement their normal purchase orders and define the R/M programs required of their subcontractors. The purchase order should state the R/M requirements levied on the subcontractor. These requirements should be consistent with the overall requirements of the system/equipment contract and should normally call for demonstration of achievement. Prior to approval by the SPO of the prime contractors R/M program or test plans the subcontractors' plans should be checked to assure that the entire program is in conformance with the system/equipment contract.

One critical point to be checked is the test and acceptance point of the subcontractors' output. Another critical point is defining responsibility for solution of interface problems. These two points should be covered clearly in the subcontractor control procedures.

h. Manuals for Training, Installation, and Maintenance. The R/M Monitor's work is not complete when the design leaves the drawing board, nor when the equipment is installed on the site. Information on proper installation, operating instructions, and maintenance procedures, both PM and CM, must be available. The initial review of these manuals should take place in-plant. Check should be made for content and format. Early evaluation can be obtained in-plant by noting use of the manuals on the test floors and in the repair departments. The technicians should be asked for comments concerning the manuals. After equipment has moved to the Category II test phase, comments of the Using and Training Commands can be obtained for further evaluation of adequacy of the manuals. The Contract Management Regions (CMRs) have specialists assigned to the district offices to assist in manual and drawing preparation. Their assistance should be requested.

i. In-House Manufacturing, Packaging, Storing, and Transporting Procedures. MIL-STD-441 establishes the basic definitions and reliability concepts for DOD. The prime consideration of the Using Commands is the "Operational Reliability", that is, what is available to them when the equipment/system is installed on site and is in the field environment. The predicted reliability obtained by using the techniques outlined in the reliability specifications such as MIL-R-26474, or the RADC Notebook, is the "inherent Reliability" which is the potential reliability that the equipment is capable of delivering. This potential reliability is degraded during the manufacturing, handling, testing, etc., phases before delivery and installation. The R/M Monitor should check the in-house procedures to see that proper consideration is given to preserving the inherent reliability. Some points that should be checked are:

(1) Receiving, stocking, storage, and issue procedures. Is the identity of equipment properly recorded and available for checking against original data? Are the bins for storage adequate to prevent damage from handling, dust, temperature, etc.? Are defective parts properly logged, tagged, sent to laboratories for analysis?

(2) Manufacturing and assembly process. Are the assembly details adequate and detailed? Are the workers properly instructed and qualified for their positions such as welding, soldering, etc? Have the techniques been checked to determine they are the best available for the particular application?

(3) Process handling. Are the assembly and transporting lines properly designed to hold and protect the equipment from dropping, bumps, and shocks? Are the assemblies tagged and identified in the processing so that process control can be checked against test results?

(4) Plant testing. Is the test equipment adequate and accurate? Are the records fully documented, dated, and verified? How are the records handled, analyzed, and tabulated?

j. Spares and Aerospace Ground Equipment (AGE):

(1) It is interesting to note that several cases have been observed where a contractor was shipping material as spares, which would not meet the specification requirements of the Prime Mission Equipment (PME). This was a result of the contract not specifically requiring certain tests on the spares that were required on the PME. In general the same requirements should be required for all spares that are called for on the "initial buy". The R/M Monitor should take advantage of the normal time lag in spares procurement to see that the problem areas noted in the "initial buy" are not repeated on "follow-on buys".

(2) As our systems become more complex and the need for higher Availability increases, the specialized AGE requirements become more complex. Adequate R/M requirements should be delineated in the SOW and provision made in the R/M plan and monitoring programs to see that the system/equipment needs are satisfied. In general, the same procedures and attention to detail should be given to the AGE as is given to the PME. Since AGE frequently requires calibration not readily available at the operating sites, arrangements should be made for calibration and check-out with the AF calibration group. If required by the system, arrangements should be made for acquisition of a Precision Measurements Electronics Laboratory thru the Newark Air Force Station, Ohio.

k. Indoctrination and Training. This element is required in most of our R/M specifications. It should be given proper consideration. The AF does expect R/M to be considered by all concerned, from the design engineers through to the shipper. The SPO should take into account the fact that, in many cases, the contractor may have had other contracts with the AF and has had similar clauses in his earlier contracts. The Monitor should check this point. He should try to determine what has already been covered and what is needed, then require the contractor to fill the gap by completing whatever training is needed to give the SPO the results desired. It is expected that when lectures or training is accomplished by the contractor, that the SPO will be given a set of the notes covering the lecture or training, with a list of attendees by name and job or function. The Government is not interested in training the contractor's commercial department at AF expense.

The Monitor may suggest several excellent films which are available through AF sources and, in addition, the Professional Technical Group on Reliability of the Institute of Electrical & Electronic Engineers will provide speakers on request. As noted earlier, this should be a specific "task" in systems contracts. If the manpower and planning on this item is known, the SPO is in a position to get the most value per dollar expended and redirect the effort if necessary.

l. R/M Math Model. The R/M Math Model (Figure I) is in effect a tool or device to determine from time to time the results achieved, and where there are trouble points. In addition, it is a means to determine where future major efforts will be needed. There are simple models and very complex ones. The contractor should develop a model that will meet the SPO purposes at least cost. It is interesting to note that some contractors have "computerized" their models. If the contract is large as well as complex, this is a good approach. By this means the R/M Engineer can readily change certain equipment/systems parameters and quickly determine the overall effect.

4. General:

a. Use of Reports:

(1) Usually each of the elements of the R/M program must be considered and be reported on regularly. Depending on the report cycle, which may be set up on a time cycle basis (monthly or quarterly) or milepost basis (Ref: Fig II) the contractor is expected to cover each element in his report. The SPO Monitor should check the progress on these items. As a convenient means of checking progress, it is suggested that a Problem List be developed as part of the report. This list should provide a quick reference of the status for the SPO/contractor effort. Development of a single uniform problem list for use by the contractor and the SPO assists in proper monitoring of the program. In this manner each problem, as reported, is entered into the list and remains on the list until resolved to the satisfaction of the SPO. A sample form for such a Problem List is shown as Figure VIII.

(2) The contractor should be advised at the start of the contract what is expected in each report in terms of content, documentation, and format.

(3) Reports should be used to assist in monitoring the program. If the reports are timely, complete, and accurate, they will indicate the progress made to date, existing and potential trouble areas. The SPO can then plan where to concentrate its efforts. In view of the personnel shortage it is important to use these reports to get a maximum value for each dollar or hour expended. Some SPOs use the "draft route" on their reports, others are formally submitted initially, with corrections to be noted in the next issue. Either method is acceptable. It is important that the reports be reviewed by the SPO for conformance with program requirements. If ommissions or errors are noted, the contractor should be advised. Normally the contractor should have SPO comments on his report ten days to two weeks after receipt by the SPO.

(4) The final report on each program should be of the summary type. It should trace the R/M history of the program noting the important developments in the cycle, the problem areas noted, and the means used to resolve them. This report should be prepared in accordance with ESD Exhibit 63-1, Volume III as a Technical Documentary Report and should be sent to the Defense Documentation Center so that the information will be available for ready reference on new procurements.

b. Records. It is highly desirable to incorporate a requirement for retention of records, data, and drawings, etc., in the prime contract. In addition, the prime contractor should be required to retain data covering subcontractor's work for a specified number of years (three years after completion of contract is suggested). There should also be

a statement time-phasing the establishment of this data file. This contractual requirement is needed due to the complexities and financial problems involved in doing business. Cases are on record where contractors have gone bankrupt either during, or shortly after completing, a contract. The result has been that the AF has items in its inventory without nomenclature, failure rates, replacement drawings, etc. This has caused major maintenance and reprocurement problems.

c. Plant Visits:

(1) There is no fixed R/M organizational requirement in Government specifications or regulations at this time, nor would a rigid requirement specifying a certain type of organization serve a useful purpose since the R/M work varies from contract to contract and is affected by the type of personnel available to do the job.

The R/M requirements of the specifications are usually developed as specific tasks (Ref: ESDP 80-2) and incorporated in the SOW. The contractor then assigns these tasks to operational elements within his organization for fulfillment. Ideally, the R/M group should be set up as a separate organizational element reporting to top management on a par with the engineering and production management groups. The organization will vary somewhat from company to company depending on the type of contract (R&D or production) and whether the prime contractor's function is primarily production or management of a given weapons program. For programs of moderate size, the following departments would be directly involved with the R/M groups:

(a) Purchasing.

(b) Incoming Inspection.

(c) Specification Control.

(d) Environmental Test.

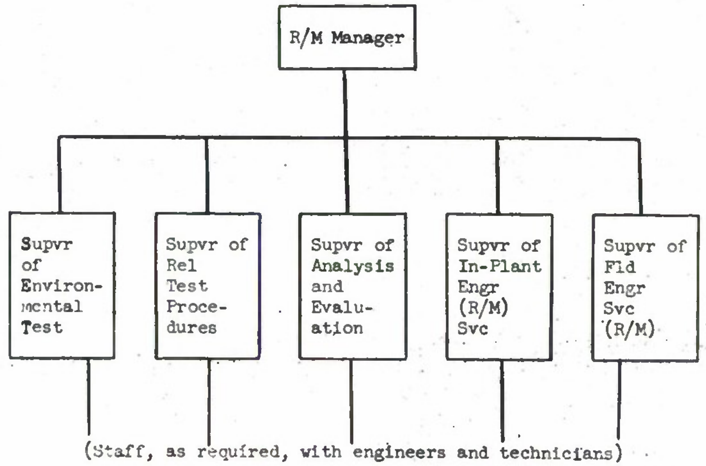
(e) Quality Control (QC).

(f) Engineering Sections (Design, Production, Test).

(g) Field Engineering (Plants and Sites).

Generally there is a close tie between the QC organizations and R/M groups. This is due to the similar nature of the work involved, especially in handling subcontractor operations and field testing. In some companies, these activities (R/M and QC) are combined under the heading of a Product Assurance (PA) Department.

The R/M Monitor should establish contact with the contractor R/M or PA Department early in the contract cycle. He should determine the degree of communication between the groups and see that the R/M group pursues their activities diligently. These contacts should result in an AF/Contractor team approach. A typical contractor R/M organization is shown below:



(2) When visiting the plant, the Monitor should visit all departments concerned with the contract. Complete answers as to R/M conditions are not found in the top management offices. The place to get the information is in the factory, in the Engineering Department, at the test benches, and at the sites. If the plant visit is made by an AF group, arrangements should be made to split the group so that one sub-group can talk to one department (i.e., Engineering) and the other to another department (i.e., Reliability). Arrange to ask each department the same questions. The sub-groups should then compare in private, or outside the plant, the answers obtained. This is an excellent means of checking intra-plant communications. A similar approach can be used by sending one man to a prime contractor's plant and one to a subcontractor's, and comparing the results to see if there is proper direction of the subcontractor by the prime contractor.

A record should be kept of all findings noted during these visits. The contractor should be advised of conditions noted and actions required. On later visits these records should be checked to see that satisfactory results are obtained.

d. Problem Resolution. If a question or problem arises with the contractor that the Monitor can not resolve immediately, the following action is suggested:

(1) Be sure the problem is clearly understood.

(2) Get any suggested solutions the contractor may wish to offer, and discuss them.

(3) Discuss any approaches the Monitor may have.

(4) Advise the contractor that the answer will be forthcoming as soon as possible after discussion at the SPO.

(5) Check for the needed information through AF sources.

(6) Advise the contractor of the decision.

Giving a prompt but unsound answer, or an erroneous one, serves no useful purpose. It may mean that AF does not get good equipment. It may mean increased costs, but most damaging of all, it gives the impression that the monitor does not fully understand the situation and can be led into making decisions. This can have serious results at a later date.

e. Assistance Available to the Monitors:

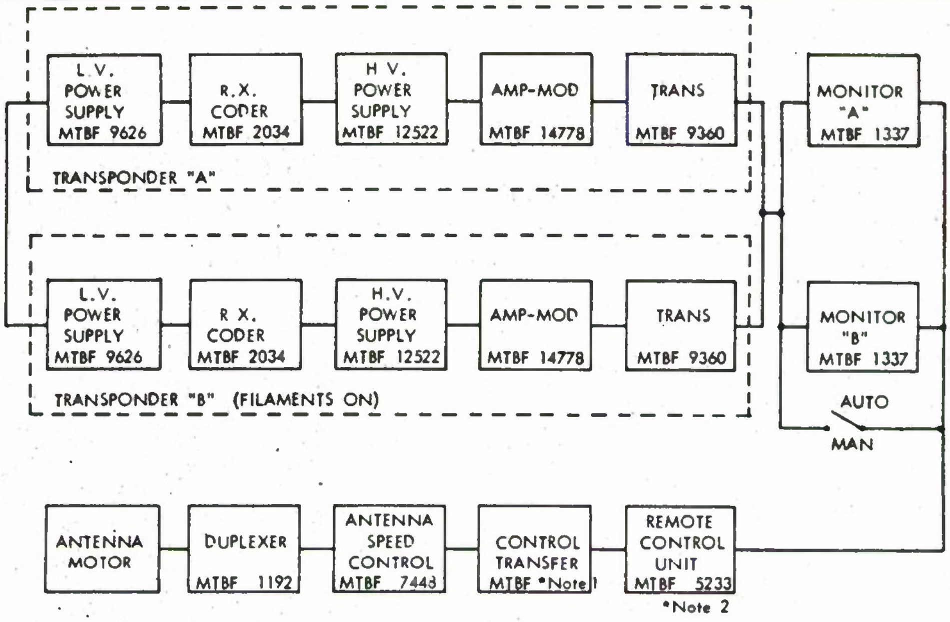
(1) RADC frequently assists the Monitor from a technical viewpoint in evaluation and review of math models, equipment monitoring, etc. The RADC Project Engineers usually have responsibility to establish performance criteria. In certain instances RADC is charged with formal acceptance for the Government. Support by RADC is established through use of "Charter Letters" (Ref: ESDR 80-2 and 80-4).

(2) The ESD R/M Staff Office (ESTE) is available for assistance in selected management and technical matters. The ESD Reliability staff normally reviews RFPs, bids, contracts, and SOWs. On occasion, assistance is available in bidders' briefings, contract negotiations, and plant visits.

(3) The CMRs have personnel assigned to various geographic and technical areas. They are available for in-plant monitoring, test verification, subcontract monitoring, manual and drawing reviews, design reviews, etc. Arrangements for CMR assistance is initiated by SPO/CMR letters of

agreement and contract delegation through the Administrative Contracting Officer.

(4) MITRE has support agreements with certain SPOs providing for engineering assistance in systems engineering matters. Limited R/M support is available under these agreements.



NOTE 1: IN LOCAL OPERATION MTBF IS 1585
IN REMOTE OPERATION MTBF IS 1180

NOTE 2: REMOTE CONTROL UNIT IS OMITTED FOR "LOCAL" OPERATION MODE

FIGURE I EXAMPLE OF RELIABILITY MATH MODEL

RELIABILITY BLOCK DIAGRAM AN/TRN-17

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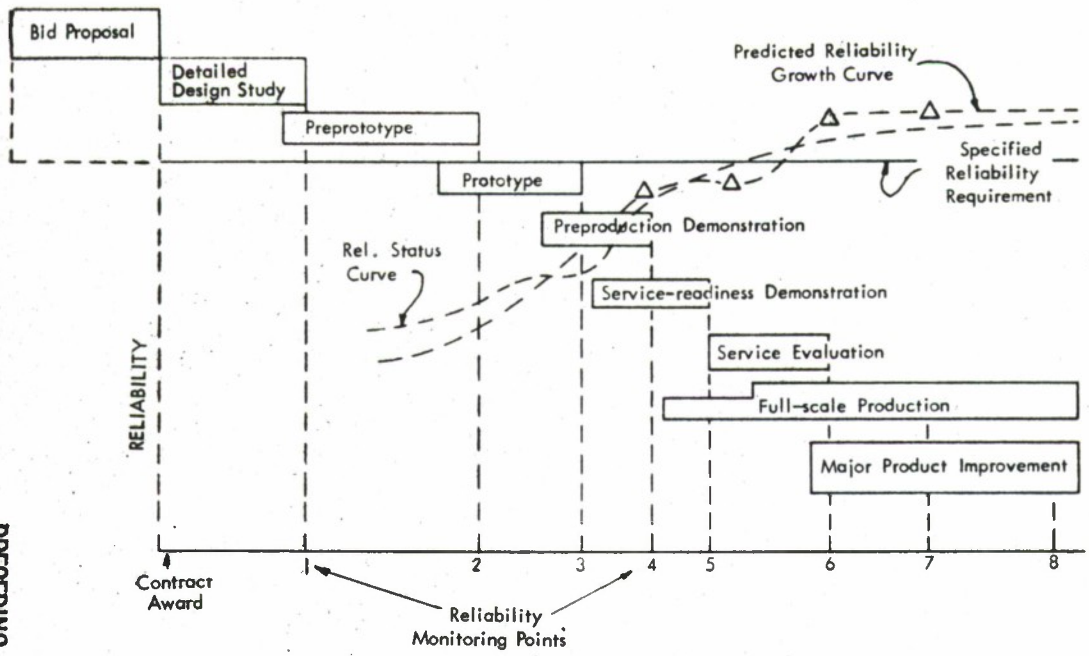

FIGURE II TYPICAL RELIABILITY GROWTH CYCLE

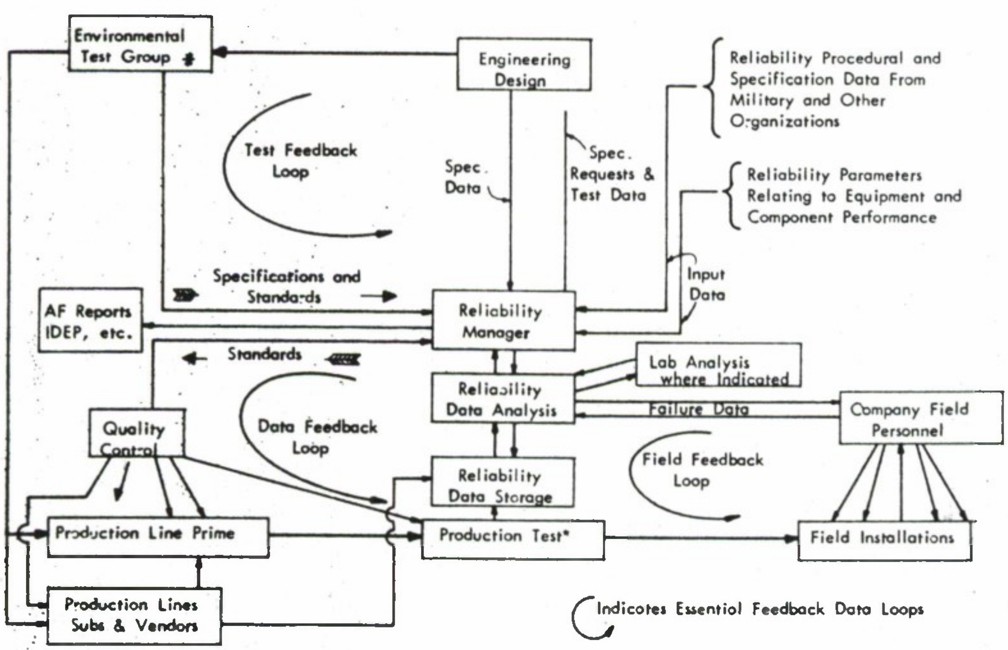

FIGURE III TYPICAL DATA FLOW DIAGRAM FOR RELIABILITY ORGANIZATION

*Production Test and Engineering Test Could Utilize the Same Facilities

1. Identifies Failure Causes - Primary or Secondary & Mode of Failure
2. Recommends Corrective Action
3. Then Follow Up on Recommendation

FAILURE REPORT

NO.

DATE OF FAILURE MO / DAY / YR	NAME OF FAILED EQUIPMENT	FAILED EQUIP. IDENT. NO.	FAILED EQUIP. SERIAL NO.
TEST OR FIELD ACTIVITY (GIVE SPEC. & PARA. NO. IF APP)		CUMULATIVE OPERATING TIME TO FAILURE HRS. MINUTES	ETI SERIAL NO.

NARRATIVE DESCRIPTION OF FAILURE (SYMPTOMS, CIRCUMSTANCES, CAUSE IF KNOWN, GIVE ADEQUATE DETAILS)

SIGNATURE	R & QA REPRESENTATIVE SIGNATURE (REPORT NOT VALID UNLESS COUNTERSIGNED)

FIGURE IV EXAMPLE OF FAILURE REPORT FORM

OPERATING TIME LOG

Page Number

EQUIPMENT NAME						EQUIPMENT IDENT. NO.					EQUIPMENT SERIAL NO.		PRECEDING PAGE NO.		
DATE MO/DAY/YR	SHIFT	START LOCAL TIME	CUM. TIME AT START	TEST OR FIELD ACTIVITY	MODE OF OPERATION OF FUNCTIONS TESTED	STOP LOCAL TIME	ELAPSED TIME THIS OPERATION	CUM. TIME AT STOP	FAILURE YES? NO	FAILURE REPORT NO	MAINTENANCE ACTIONS	REMARKS	SIGNATURE	INITIALS REP. CONTRACTOR	AF

FIGURE V EXAMPLE OF OPERATING TIME LOG

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A. JOB CONT NO	B. PRI	C. TIME SPEC REQ	D. WK AREA	E. EST M/H	F. ORIG RPT NO	G. REPORT NO	H.	I.

1. WEAPON TMS	2. SERIAL NO	3. TIME	4. WORK CENTER	5. WORK ORDER NO	6. DAY MO YR	7. WORK UNIT CODE

1A. AGE WUC	2. SERIAL NO	3A. TIME	8. ACT TAKEN	9. WHEN DIS	10. HOW MAL	11. UNITS	12. LABOR HOURS	13. ASST WORK CENTER

1B. ENG TM PSN	2B. SER MOD YR-MFG SERIAL NO	3B. TIME	14. INST ENG TM PSN	15. SER MOD YR-MFG SERIAL NO	16. TIME

1C. ITEM FSC	2C. PART NO	3C. SERIAL NO	17. INST ITEM PT NO	18. SERIAL NO	19. TIME

J. SYMBOL	K. DISCREPANCY	L. CORRECTIVE ACTION

SUPPLEMENTAL DATA

21. TASK START NO	22. FAILED ITEM NOUN	23. FAILED ITEM MFG	24. NEXT ASSY P/N	25. NEXT ASSY S/N	26. NEXT ASSY NOUN	27. NEXT ASSY MFG

28. OPERATIONAL TIME AT FAILURE				29. SEVERITY OF FAILURE			30. TYPE FAILURE		31. ANAL REQ		32. FAILED ITEM DISPOSITION	
HRS MIN SEC A	CYCLES B	CAL TIME C	MILES D	CRITIC A	MAJOR B	MINOR C	PRIM A	SEC B	YES A	NO B	ELIM A	FIELD SERVICE B

33. MAINTENANCE TIME			34. NO PERSONS USED	35. EQUIV AFSC	36. T. O. PROCED NO		37. USE OF SPECIFIED TOOLS		
TOTAL DOWN TIME A	ACTUAL REPAIR TIME B				ADEQ A	INADEQ B	ADEQ A	INADEQ B	NOT NEEDED C
	TROUBLE SHOOT	REPAIR							

38.	39. FOLLOW-UP AGENCY ☐ QC ☐ ENG ☐ OTHER	40.	41.

42. AF/CONTRACTOR USE

	CORRECTED BY-SIGNATURE & GRADE

	DISCOVERED BY-SIGNATURE & GRADE	INSPECTED BY-SIGNATURE & GRADE	SUPERVISOR-SIGNATURE & GRADE

RECORDS ACTION ☐ UNCLEARED DISCREPANCY ☐ REPLACEMENT TIME CHANGE ITEM ☐ DATA TRANSCRIBED TO APPROP RECORDS	DATE TRANSCRIBED	TRANSCRIBED BY-SIGNATURE & GRADE

FIG VI- MAINTENANCE DISCREPANCY/PRODUCTION CREDIT RECORD

(SEE REVERSE)

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20. PARTS REPLACED DURING REPAIR

FSC	PART NUMBER	WORK UNIT CODE	REF SYM	HOW MAL	QTY

REPAIR CYCLE DATA	1. DATE REMOVED	2. RECEIVED IN BASE SUPPLY	3. SHIPPED TO SRA	4. RECEIVED AT SRA	5. ORDERED BY MAINTENANCE	6. RECEIVED IN MAINT SHOP	7. MADE SERVICEABLE

FIGURE VI-A MAINTENANCE DISCREPANCY/PRODUCTION CREDIT RECORD

Reliability/Maintainability Modification Analysis Report

Equipment:

Description   Drawing No.

Manufacturer

S/N

Propose to Start with Equipment No. ___________
Estimated Cost/Unit ___________

Modifications (list and explain; attach drawings)

1.

2.

3.

4.

Analysis

Modification No.	Condition (See Modification Analysis Chart)	Value* (MTBF) R	Figure of Merit R	Remarks
(1)				
(2)				
.				
.				
.				

*Note: Attach all data and computations   (See Reverse)

FIGURE VII EXAMPLE OF MODIFICATION ANALYSIS SUMMARY FORM

R/M Qualitative Modification Analysis Chart		
CONDITION	**RELIABILITY**	**MAINTAINABILITY**
A	Favorable	Favorable
B	Favorable	Adverse
C	Adverse	Favorable
D	Adverse	Adverse
E	No effect	Adverse
F	No effect	Favorable
G	Adverse	No effect
H	Favorable	No effect
I	No effect	No effect

FIGURE VII-A MODIFICATION ANALYSIS CHART

CORRECTIVE ACTION FOLLOW-UP REPORT

PROGRAM ______
DATE ______
PAGE ______ OF ______

FAILURE				CORRECTIVE ACTION			
RPT. NO.	DATE	REPET-ATIVE	DESCRIPTION	DESCRIPTION	ASSIGNED TO	DUE DATE	STATUS

FIGURE VIII EXAMPLE OF CORRECTIVE ACTION FOLLOW-UP REPORT

APPENDIX

Development of Circuit/System Mathematical Model

1. The essential steps in development of a mathematical model are given below. While the procedure given deals with relatively simple configurations, the principles involved also apply to the most complex equipment/systems. Attachment 1 gives the Reliability Functions for Various Active-Parallel Configurations.

Step 1 -
Define the equipment/system in terms of its required functions.

Step 2 -
Construct the Reliability Block Diagram. To do this, the equipment/system must be analyzed in terms of its parts (subordinate elements) showing the "Reliability Paths" through which the desired function will be accomplished.

Step 3 -
Describe the reliability block diagram in terms of its success/failure probabilities. Separate statements should be developed for each path or mode of operation.

Step 4 -
Estimate the Reliability of the individual parts or elements in reliability block diagram. This can be based on standard failure rates (RADC notebook), results obtained with similar equipment, or actual test results. Failure rates should be adjusted based on the environmental application and stress levels used.

Step 5 -
Obtain the numerical value (Probability of success (P)) of the equipment/system.

2. The following points should be noted in the development and application of the mathematical model:

a. Depending on the accuracy of the results desired low failure rate items, such as, tube sockets, terminal strips, etc., may be omitted from the calculations.

b. If equipment/system can operate in alternate modes, these must be considered separately.

c. Consideration must be given to types of redundancy involved (active, stand-by, etc).

d. If the overall equipment/system Reliability value finally obtained does not meet requirements changes can be made by studying the "weak links." These may be improved by adding redundant elements, additional derating, using improved parts, etc.

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e. The same type of analysis can be used for evaluation of other system parameters, such as, cost, volume, weight, effectiveness, etc.

f. In development of failure rates, certain "K" factors may be needed to compensate for environments, such as, airborne vs ground-operated equipment or changes in duty cycles.

3. The basic system configurations are shown below. All equipment/systems can be resolved into similar configurations for problem solution. In the examples given, the following notations are used:

R_s = probability of success or reliability of a system or block.

r = probability of success or reliability of a unit or path.

p_i = probability of success or reliability of element i.

q_i = probability of failure or the unreliability of element i.

(NOTE: $p_i + q_i = 1.0$)

Elements of a system/equipment are designated as A, B, C, etc. For probability statements concerning element success or failure, the following notations are used:

(A) = the event or success of element A.

P(A) = probability that event A occurs p_a.

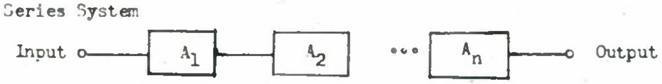
ij = the element in the i th row and j th column where i = 1, 2, etc; j = 1, 2, etc.

$p(t)$ = element reliability function = $\int_t^{\infty} f(t)\,dt$

$q(t) = 1 - p(t)$ = element unreliability function.

When elements have an exponential failure density with failure rate λ, then the reliability function $p(t) = e^{-\lambda t}$ and the unreliability function = $q(t) = 1 - e^{-\lambda t}$

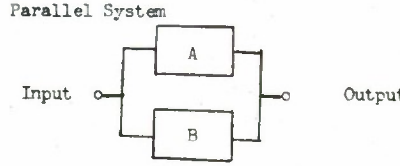
a. Series System



Rel system = $P(A_1) \cdot P(A_2)$ ... $P(A_n)$

Where P = Probability that **A** will operate. In this system to achieve success, all elements must operate.

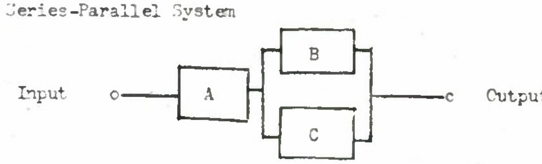
b. Parallel System



Rel System = $P(A) + P(B) - P(A) \cdot P(B) = R_s$

In this system, success is achieved if A and/or B is operable.

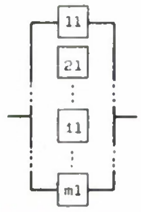
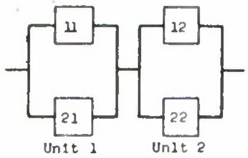
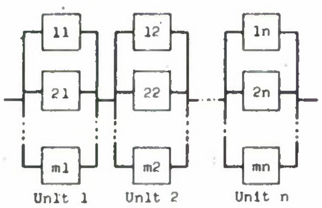
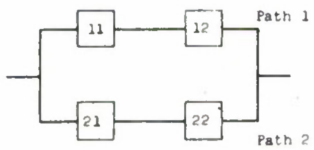
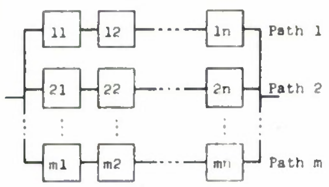
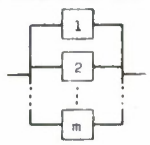
3. Series-Parallel System



$R_s = \left[P(A)\right] \cdot \left[P(B) + P(C) - P(B) \cdot P(C)\right]$

In this system, to be successful, A must be operable plus B and/or C.

RELIABILITY FUNCTIONS FOR VARIOUS ACTIVE-PARALLEL CONFIGURATIONS

Reliability Block Diagram	Configuration	Reliability Function, R(t)	Exponential Mean Life, θ
	1. Basic Series a) General Case	$p_{11}(t)\ p_{12}(t)\ \cdots\ p_{1n}(t)$	
	b) Identical Elements	$p(t)^n$	$\frac{1}{n\lambda}$
	2. Basic Parallel a) General Case	$1 - q_{11}(t)\ q_{21}(t)\ \cdots\ q_{m1}(t)$	
	b) Identical Elements	$1 - q(t)^m$	$\frac{1}{\lambda}\sum_{i=1}^{m}\frac{1}{i}$
	3. Series-Parallel 2 x 2 a) General Case	$\left[1-q_{11}(t)q_{12}(t)\right]\left[1-q_{21}(t)q_{22}(t)\right]$	
	b) Identical Units	$\left[1-q_1(t)^2\right]\left[1-q_2(t)^2\right]$	
	c) Identical Elements	$\left[1-q(t)^2\right]^2$	$\frac{11}{12\lambda}$
	4. Series-Parallel m x n a) General Case	$\prod_{j=1}^{n}\left[1-q_{1j}(t)q_{2j}(t)\cdots q_{mj}(t)\right]$	
	b) Identical Units	$\prod_{j=1}^{n}\left[1-q_j(t)^m\right]$	
	c) Identical Elements	$\left[1-q(t)^m\right]^n$	$\frac{1}{\lambda}\sum_{j=1}^{n}\left[(-1)^{j+1}\binom{n}{j}\sum_{i=1}^{jm}\frac{1}{i}\right]$
	5. Parallel-Series 2 x 2 a) General Case	$1-\left[1-p_{11}(t)p_{12}(t)\right]\left[1-p_{21}(t)p_{22}(t)\right]$	
	b) Identical Paths	$1-\left[1-p_1(t)^2\right]\left[1-p_2(t)^2\right]$	
	c) Identical Elements	$1-\left[1-p(t)^2\right]^2$	$\frac{3}{4\lambda}$
	6. Parallel-Series m x n a) General Case	$1-\prod_{i=1}^{m}\left[1-p_{i1}(t)p_{i2}(t)\cdots p_{in}(t)\right]$	
	b) Identical Paths	$1-\left[1-p_1(t)p_2(t)\cdots p_n(t)\right]^m$	
	c) Identical Elements	$1-\left[1-p(t)^n\right]^m$	$\frac{1}{n\lambda}\sum_{i=1}^{m}\frac{1}{i}$
 At least k elements required	7. Partial Redundancy Require at least k satisfactory elements a) Identical Elements	$\sum_{i=k}^{m}\binom{m}{k}\ p(t)^k\left[1-p(t)\right]^{m-k}$	$\frac{1}{\lambda}\sum_{i=k}^{m}\frac{1}{i}$

SECTION VIII

RELIABILITY AND MAINTAINABILITY PROBLEMS OBSERVED DURING CONTRACTOR MONITORING

SECTION VIII

RELIABILITY AND MAINTAINABILITY PROGRAM PROBLEMS OBSERVED DURING CONTRACTOR MONITORING

FOREWORD

The purpose of this section is to set forth twelve major problems observed by the OPR and SPO R/M Engineers during the course of monitoring contractor R/M Programs.

These problems were observed over the past year and a half. In each case, the SPOs involved have required corrective action by the contractors.

The contents of this section serves as a guide for new SPO R/M Engineers in the prevention of similar problems on their program.

SECTION VIII

CONTENTS

RELIABILITY AND MAINTAINABILITY PROGRAM PROBLEMS
OBSERVED DURING CONTRACTOR MONITORING

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1. Introduction:

Contractor R/M programs conducted in accordance with existing Air Force specifications require a vigorous monitoring by the involved SPOs.

During the past year and a half, the OPR and various SPO R/M engineers have been complying with this Air Force requirement. This activity has served to identify certain contractor practices which must be avoided, if R/M programs are to be successful.

Twelve of these practices are identified in paragraph 2 below. New SPO R/M engineers will take the necessary action to avoid their occurrence on future SPO programs.

2. R/M Program Problems:

a. Lack of a Well-Organized Equipment Design Review Effort. Current R/M programs require periodic formal design reviews. The main purpose of such reviews is to detect and eliminate potential causes of unreliability and/or unmaintainability early in the program. The cost involved in making changes during the design phase of a program has been estimated to be 1/1000 of the cost involved after equipment delivery to the Air Force. A vigorous engineering design review effort must be accomplished by contractors.

This effort involves identification of the contractor personnel and/or organizations involved in design reviews, responsibilities and authorities of a Design Review Board, frequency (of design reviews), and approach to conduct of reviews.

A Board is expected to maintain minutes of meetings and to assign corrective action follow-up responsibilities.

Reviews of contractor R/M programs have served to identify instances of no company policy on design reviews and no organizational responsibility for design reviews. A systematic approach to design reviews should involve the use of a design review checklist. The absence of such a checklist was noted in almost all the programs reviewed

b. Failure to Incorporate Quantitative Reliability Requirements in Subcontractor Specifications. The attainment of a specific quantitative reliability level in a complex system/equipment requires that a prime contractor specify firm quantitative requirements in subcontractor equipment specifications.

Paragraph 3.5.5 of MIL-R-27542A (USAF) states that:

"The contractor shall impose, directly or indirectly, quantitative reliability requirements and acceptance criteria on all echelons of suppliers and subcontractors.

"The contractor shall take all actions necessary to assure that no changes made by any supplier will reduce reliability of the system."

c. Spasmodic Communication Between R/M and Design Engineering. Frequently, contractor R/M organizations have seemed to operate independently of other contractor organizations, such as, design engineering; e.g., basic recommendations on application of piece parts to minimize failure rates have been found to be sketchy. No established channels of communication for informal discussions on R/M design problems seemed to be the rule.

The communication problem is considered to be a management rather than a technical consideration. Unless contractor management takes action to foster such communication, independent or quasi-independent operations will continue to the detriment of Air Force product reliability.

d. Poor Corrective Action Procedures. Absence of well coordinated corrective action efforts have been observed. Identified R/M problems have not been properly scheduled for corrective action. Follow-up to assure problem resolution was lacking. In certain cases, system/equipment engineers were not even aware of the existence of R/M problems. Failure data analysis by itself will not improve equipment R/M. It is necessary to supplement such analysis with a corrective action effort which assures that identified R/M problems or "weak-links" are resolved.

e. Late Reports. Monthly reports on R/M have been found to be as much as six weeks late. The result, of course, is that SPOs have late information for decision-making on the progress of R/M programs.

Furthermore, contents of reports have been found to be of questionable R/M management value, e.g., "weak-link" tables, with corrective action schedules, have been noticeable by their absence. Trend curves which indicate equipment MTBF "growth" have not been presented.

f. Lack of "Ground-Rules" for Failure Data Reduction. Several system/equipment programs were found to have quantitative reliability requirements but no agreements as to failure definitions or method(s) of data reduction. Furthermore, it was not clear as to whether or not the quantitative requirements referred to inherent or operational reliability.

In other words, the involved SPOs had no clear-cut process of determining compliance or lack of compliance with quantitative requirements.

The specification of numbers without corresponding data collection and reduction ground-rules is considered to be an unsatisfactory arrangement.

g. Vague Bases for Trade-offs. Frequent references to trade-offs between reliability and maintainability system/equipment characteristics without a determination of quantitative effects of such actions appeared as a consistent pattern on programs which incorporated quantitative availability requirements.

h. Lack of Quantitative Data on ECPs. Computations of the quantitative effects of proposed changes on system/equipment R/M capability were found to be deficient. In several situations, when quantitative effects were presented, back-up data, and mathematical techniques were absent.

In several cases, the contractor's R/M organization was not aware that an ECP was processed or was being processed.

i. Unsatisfactory Mathematical Models. Examples of contractors assuming a simple series reliability model, when the system/equipment contained alternate modes and/or redundant replacements, have been observed. This, of course, led to inaccurate representations of equipment capability. While simplicity in mathematics is desirable, validity is considered essential.

j. Unsatisfactory R/M Predictions. As a design progresses and as failure and repair data is collected and processed, predictions of system/equipment R/M capability should involve less assumptions. For example, initially it is necessary to make assumptions as to how parts are to be operated, and the stress levels to be experienced. As the design progresses, information becomes available as to actual design margins of safety which influence the failure rates of parts. Later, it is possible to gather information on actual stresses from engineering breadboard and environmental tests which again influence failure rates.

Certain prediction reports have been reviewed where, after several years of work on a program, assumptions were being made about part margins of safety and operating environments. Furthermore, final prediction reports have been studied where the contractor continued to assume a mission profile.

In other words, the involved contractors failed to take advantage of increased information to modify and update their prediction techniques.

k. Late Submission of R/M Program Plan. While contracts have called for submission of program plans 30 or 45 days from award of contract, submittal dates have been ignored in large number of cases. Also, upon receipt of proposed plans, it was noticed that several SPOs had not given official approval of the plans following SPO review. Failure to give such approval leaves contractors in doubt as to whether or not to proceed with the R/M programs.

1. Lack of Coordination Between R/M and Logistics Groups. Failure of these activities to coordinate their work, results in improper support of the system from a spares, AGE, and maintenance viewpoint. If R/M does not assist the logistics group in determining levels of support needed, based on failure and repair rates, the usual result is improper loading of these aspects of the system. Parts are procured on "percentage basis" and have no relation to actual consumption rates effected by good or poor design factors. On continuously operating systems such as those developed by ESD, the preventive maintenance cycle requirements are a key factor in determining availability. Lack of coordination results in "poor guesses" rather than "good models."

SECTION IX

GUIDANCE ON INCENTIVE CONTRACTING FOR RELIABILITY

SECTION IX

GUIDANCE ON INCENTIVE CONTRACTING FOR RELIABILITY

FOREWORD

The purpose of this section is to provide guidance to SPO Reliability and Maintainability (R/M) Monitors on the use of contract incentives for reliability.

Identified are several technical problems that arise when developing reliability incentives; some suggested solutions are provided.

SECTION IX

CONTENTS

1. Introduction:

Communications received from Hq Systems Command (see Attachment 1) have expressed a concern over the general inadequacy of contractual provisions for the assurance of system/equipment reliability. Other correspondence, particularly directives emanating from DOD, have specified the use of incentive-type contracts in lieu of the traditional cost-plus-fixed-fee (CPFF) contracts for procurement of weapons systems. The purpose of this document, then, is two-fold, as follows:

a. To provide the ESD SPOs with guidance on the inclusion of certain contractual provisions which emphasize contractor obligations associated with attainment of specified system/equipment reliability.

b. To provide general guidelines for stipulating reliability incentive requirements and identify certain technical problems that arise in the process of doing so. Suggested solutions for some of these problems are also provided.

In discussions which encompass more than one area or specialty, e.g., reliability engineering and contract administration, there usually arises a need to establish a common communications in order to avoid misinterpretation of meaning of words. To minimize the problem in the discussion to follow, therefore, when a word or phrase which is unique to one specialty is used, it will be followed parenthetically, whenever necessary, by the appropriate expression unique to the other specialty.

2. Reliability Clause For Firm Fixed Price Contracts:

ESD policy is that all system/equipment contracts will contain minimum, numerical reliability requirements (minimum acceptance reliability); these requirements are usually expressed in terms of mean-time-between-failures (MTBF). Additionally, it is ESD policy that contractual provisions will include the requirement for the demonstration of the stated quantitative requirements at selected program milestones.

These policies are based on the requirements of AFR 80-5, Reliability Program For Systems, Subsystems, and Equipments, dated 24 August 1964. Specifically, paragraph 4.b of AFR 80-5 states in part: "Specifications, exhibits, work statements, product descriptions, and contracts for systems and associated material, including Government Furnished Equipment (GFE) for inventory, will include specific minimum acceptance reliability requirements as one of the major engineering factors."

In addition, paragraph 4.f states: "Reliability tests, evaluations, or measurements will be conducted under conditions specified by the proposal or any subsequent test plan approved by competent authority. If contractual reliability requirements are not met during the demonstration tests, the deficient portions of the system shall be redesigned at no additional contract cost and the demonstration tests continued or repeated to verify that acceptance

<u>reliability has been achieved. In the event such corrective action proves impossible or impractical, consideration shall be given to assessing monetary penalties and unit price decreases or, alternately, instituting default action under the contract</u>."

Insomuch as AFR 80-5 requires of procuring activities that appropriate reliability requirements be included in contractual documentation, it remains for the SPO to assure that these requirements in fact <u>are included</u>. This requires that numerical requirements and demonstration of these requirements are clearly stipulated; it requires that alternatives are provided which specify courses of action upon non-compliance, i.e., "rejections and retest". Although the extent to which the legal responsibilities of a contractor (concerning non-compliance) have been questioned by some SPO personnel, Armed Services Procurement Regulation (ASPR) Section VII provides us with provisions for inclusion in the General Provisions of a Supply Contract, namely: Paragraph 5-Inspection; Paragraph 11-Default; and Paragraph 12-Disputes. These three paragraphs are incorporated in Attachment 2. Briefly, Paragraph 5-Inspection, states: "(a) All supplies (which term throughout this clause includes without limitation raw materials, components, intermediate assemblies, and end products) shall be subject to inspection and test by the Government--including the period of manufacture, and in any event prior to acceptance. (b) In case any supplies or lots of supplies are defective in material or workmanship <u>or otherwise not in conformity with the requirements of this contract</u>, the Government shall have the right either to reject them--or to require their correction. Supplies or lots of supplies which have been rejected or required to be corrected shall be removed or, -- corrected in place by and at the expense of the contractor --. (c) The Government reserves the right to charge to the contractor any additional cost of Government inspection and test--when reinspection or retest is necessitated by prior rejection." It is the responsibility of the SPO Contracting Officer to include the above ASPR clauses in the contract; the SPO R/M Monitor should take a personal interest to assure that they are included.

3. <u>Considerations For The Reliability Incentive</u>:

As indicated in paragraph 1, it has become apparent that more and more emphasis is being placed on the "incentive" type of contract in lieu of the cost-plus-fixed-fee type. Several DOD guidance documents have been published on the use of incentive contracting. Although that which follows pertains to incentive contracting in general, it provides the basic concepts by which consideration is established for reliability incentives.

DOD Incentive Contracting Guide (AFP 70-1-5) provides this reason for the increased emphasis on incentive contracting: "From 1953 to 1961 the dollar value of missiles and electronics increased from 12 to 52 percent of total hardware deliveries. The reason?--a rapidly changing technology and expanding requirements for even more complex weapons had radically altered the character and function of military research and development. No longer the low-cost predecessor of large, relatively stable production runs, R&D had

become a substantial cost factor in the evaluation of every weapons system." To carry this statement further, it seems to have become the rule at ESD that the system (hardware) that is evolved during an R&D effort becomes <u>THE</u> system that is specified for operational deployment; hence, the principle of concurrency. Therefore, the initial design must be the right one since there is no "second chance" to do things better, including increasing the degree of reliability, except by way of ECP.

"The incentive principle holds, in brief," so states the DOD guide, "that a contractor should be motivated in calculable monetary terms, (i) to turn out a product that meets significantly advanced performance goals, (ii) to improve on the contract schedule up to and including final delivery, (iii) to substantially reduce the costs of the work, or (iv) to complete the project under a weighted combination of some or all of these objectives." The literature is quick to caution, however, that the performance incentive (including reliability) will <u>not</u> be used, under any circumstances, as a substitute for a clear definition of the desired end item. It is not intended to place in the hands of the contractor or the SPO broad trade-off decisions regarding the final performance outcome of the program. What it <u>does</u> require is the precise specification of the nominal performance results that are desired. In this light, the performance incentive emerges not as a means of turning the program into a "profit game" operating between very wide limits, but simply as an inducement to the contractor to meet or exceed the nominal performance requirements set forth by the SPO. In fact, where the achievement of target (minimum acceptance) performance is of extreme importance, intentional trade-offs that sacrifice performance for the sake of cost savings should be prevented. Additionally, a contract clause should be included that provides for the loss of all earned cost rewards unless performance meets or exceeds target (minimum acceptance) levels.

In evaluating the above as to the effects on providing incentives for reliability as a part of the overall CPIF contract structure, several factors must be considered:

a. Reliability incentives should be used as an inducement to the contractor to meet or exceed the required degree of reliability. In accomplishing this end, it may require that the contractor provide more conservative design through circuit simplification; utilize greater margins of safety for parts application and/or high reliability (MINUTEMAN) parts; or apply simple redundancy. Reliability incentives require that studies must be performed, therefore, to determine the levels of reliability required to satisfy mission requirements; whether these levels are, in fact, attainable within design state-of-the-art; and what the potential operational support savings would be if hardware reliability were greater.

b. The use of reliability incentives should provide a contractor some degree of flexibility by allowing for trade-offs between various performance parameters. This would require the contractor to optimize on each parameter in order to arrive at the highest potential incentive. Suppose, as a simple illustration, that a certain SPO mission requires a level of system "Availability" which can be satisfied with reliability (MTBF) of 60 hours and

maintainability (MDT) of two hours. It is known as a result of study that each parameter is the optimum that can be achieved by application of existing state-of-the-art design techniques. These values, then, would be specified as the minimum acceptance values (or target values). Further, suppose that the SPO can determine witb some degree of accuracy, what operational support savings could be realized during the useful life of tbe system if the MTBF were higher and/or the MDT lower, and is willing to share the savings witb tbe contractor. The contractor would then be motivated to exploit his technical resources to design a system, optimizing on MTBF and MDT above minimum requirements to the point where his additional design and production costs equal, or are less than, the incentive (fee) return. Of course, there are those values of MTBF and MDT which become economically impractical (because of budget limitations) for tbe SPO to pursue. Additionally, development costs may exceed the potential support savings (see figures 1 and 2). These values, essentially plateaus, would be used by the SPO in structuring the incentive plan.

c. As is the case in any type of contract, the use of incentives for reliability requires that extreme care is exercised in the specification of the quantitative requirement (minimum acceptance; target) and each objective level. Definitions must be provided for such terms as malfunction, failure, and operating time, both at the equipment and system levels, as applicable. In addition, it must be clear, and mutually agreeable to botb the SPO and the contractor, as to how the test data is to be collected, who is to collect it, who is to reduce the data, and how it will be reduced. It must also be initially agreed who is to operate the equipment, what the test conditions will be, and how many equipment/systems are to be in the test sample.

d. Demonstration of attained levels of reliability presents difficulties which are somewhat unique to the use of incentives. Whereas a fixed-price type of contract may require the application of a relatively simple sequential test to demonstrate the "minimum acceptance reliability" (one value), demonstration of reliability in an incentive contract requires a degree of flexibility to allow for the determination of having achieved a certain reliability value within a specified range of values. The problem is compounded furtber when one is confronted with having to demonstrate, with a relatively higb degree of statistical assurance, the reliability of a multi-moded command and control system rather than a simple piece of equipment. Paragraph 5 further discussed the problems associated with demonstration.

4. Reliability In Multiple Incentives:

Traditionally, multiple incentives have encompassed three major areas of concern: performance; costs; and schedules, where the total incentive fee is apportioned in some manner to each major factor. The purpose of combining incentives is obvious. Successful performance of almost any contract consists of completing a satisfactory end item or service at a reasonable cost and within certain time limits. Since all these factors are closely dependent on each other, a contract that places too heavy a premium on one risks a loss of control over the other two. It follows, then, that a properly structured multiple-incentive contract should serve two basic purposes:

Relationships Between
Cost for Reliability and Operating Costs

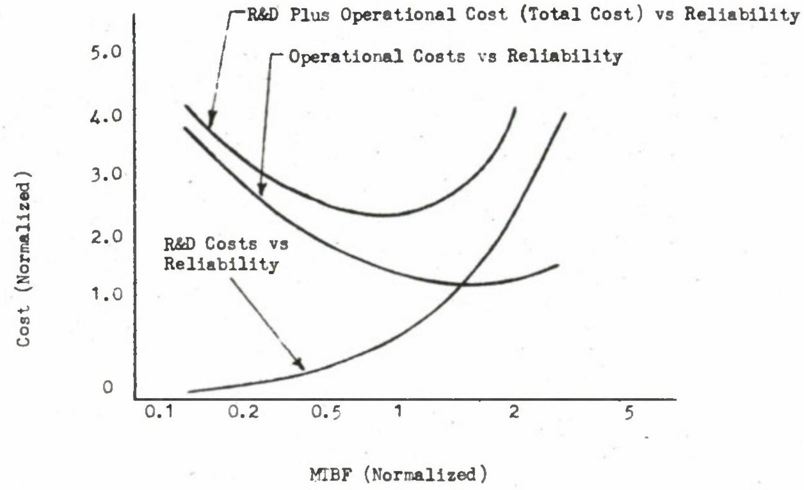

Figure 1

The total cost of a system is tbe sum of initial design-for-reliability investment and operational costs. The opposite slopes of these two factors produces the minimum cost "saddle" in the total cost curve.

Relationship Between Total Costs and Level of Reliability

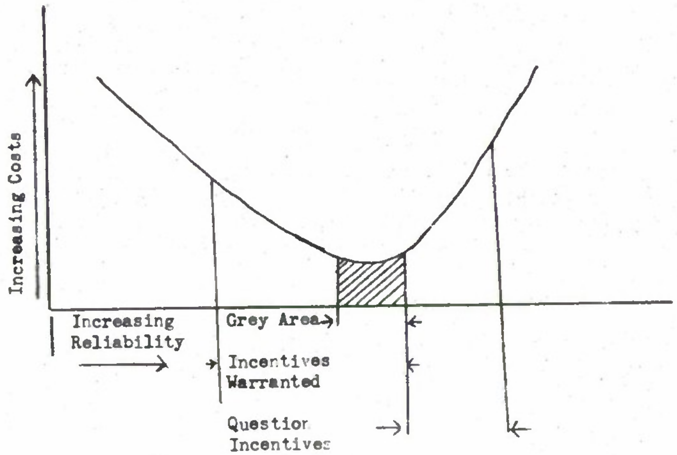

Figure 2

Too little or too much investment in initial reliability can be expensive when considered on the basis of total system cost (includes both procurement and support costs). Incentives are warranted only in those areas where the present reliability of the type of system can be economically improved.

a. It should motivate the contractor to strive for outstanding results in all three incentive areas. In other words, his objective at the outset should be to earn maximum profit, and the contract should be structured so that there is some possibility that he can do this.

b. The incentive structure should compel decisions between cost, time, and performance that are consistent with the overall procurement objectives of the SPO when it becomes apparent to the contractor that outstanding results cannot be achieved in all areas.

Realization of the first objective depends largely on the range of effectiveness (minimum acceptance to maximum, or objective, values) established for each incentive element and the probability of achieving outstanding performance in all incentive areas. On the other hand, realization of the second purpose is based mainly on the relative weights assigned to each incentive element since weights, along with the separate ranges of effectiveness, will establish the various break-even points for trade-off decisions between cost, schedules, and performance. A major consideration, then, is how these two factors—relative weighting and range of effectiveness—are to be determined for a given situation, and more specifically, the manner by which the incentive for reliability is established.

Just as the minimum acceptance reliability requirements must be established in a fixed-price contract, so is the case when incentives are contemplated. In fact, when the range of effectiveness is developed, the lower limit of the range is set by the SPO as being a minimum acceptance reliability value which will be satisfactory even if a contractor does poorly on this incentive element. Therefore, care should be taken to set this minimum value at a level such that it will, in fact, be satisfactory if that is all that is delivered in the equipment. On the other hand, the upper reliability limit of the effectiveness range should represent the maximum reliability value attainable within the scope of the plans and contractor proposals developed during program definition, or as a result of SPO program planning activities.

Included in Paragraph 3 was a brief indication that reliability is one characteristic usually included as a performance factor; other characteristics include speed, weight, space, accuracy, range, etc. This could mean, then, that when the performance factor incorporates more than one characteristic, the weight given to any one characteristic approaches an insignificant level when considered within the total incentive structure, and may become unattractive for a contractor to pursue. Take the hypothetical case wherein the performance factor is apportioned 25 percent of the total incentive. If the performance factor is comprised of four equally-weighted characteristics (one of which is reliability), then any one of them would be afforded slightly more than six percent of the total, potential incentive fee. It would seem then, that a contractor would find it more appealing to disregard those areas where small incentive fees could be achieved and, rather, pursue the cost and schedule incentive factors which yield the greater fees. The very fact that the reliability characteristic was chosen to be incentived should indicate that it was highly desireable to achieve greater reliability

than is normally achieveable through the application of standard techniques. In turn, an appropriate weighting should be afforded to it, not as a part of the performance factor, but in terms of the total multiple incentive structure; some contend that it should be in the order of 15 to 30 percent of the total incentive fee.

5. Reliability Demonstration and Incentives Formulation:

A search of existing ESD contracts indicates that most existing incentive contracts have dealt with cost incentives alone. Summarized briefly are several interrelated reasons for the absence of reliability incentives:

a. The difficulty in defining the reliability requirements.

b. The principle of concurrency which does not always permit meaningful reliability demonstration testings.

c. The absence of demonstration models for high MTBF situations.

d. The tendency of government negotiations to ignore compliance to reliability requirements during contract negotiations.

As mentioned earlier, the term "reliability" is absolutely without contractual meaning unless clearly defined. Any definition of reliability in terms of "satisfactory performance" is not adequate by itself. Reliability or statistical probability must be defined in terms of demonstration conditions and methods, risks and confidences, and success and failure, etc. Therefore, it is useless to begin a profit determination or an incentive negotiation for reliability unless both contractor and ESD are first able to agree on demonstration, and validity of demonstration or the conditions under which collected data will be acceptable or unacceptable for computational purposes.

The quantities or values to be selected for upper and minimum (lower) acceptance reliability constitute the range of "incentive effectiveness"; ESD must establish these values. Once the range of incentive effectiveness has been established, the actual incentive aspects are in a position to be negotiated. Several patterns may be established for this formulation. Figure 3 displays fee-reliability relationship. Figure 4 displays a progressive incentive relationship.

Both figures indicate:

a. A system of rewards and penalties.

b. Establishment of an MTBF incentive range of effectiveness.

c. Establishment of a target (minimum acceptance) MTBF. Here, no effect on target fee results if this value is demonstrated. (That is, the target fee, but no additional fee, is provided.)

Linear Relationship for Incentive With Reward and Penalty

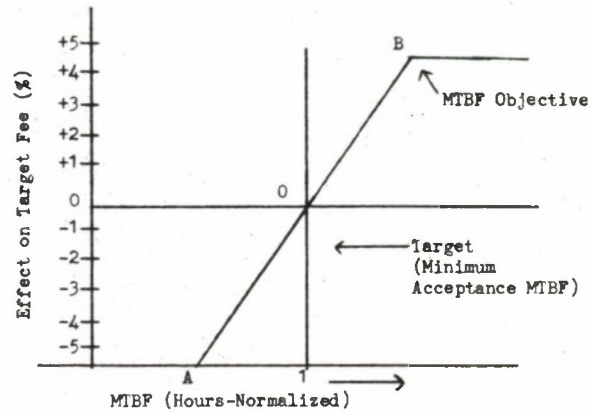

Figure 3

Progressive Relationship for Incentive With Reward and Penalty

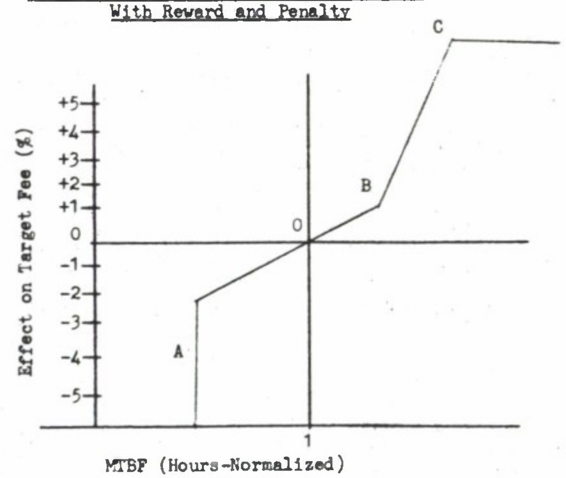

Figure 4

As a numerical example, assume a target (minimum acceptance) reliability of 90 percent, a range of effectiveness of ± 4 percent, a target fee of 6 percent, and fee swing of ± 4 percent. Based on this information, Figure 3 is restructured as follows:

Linear Relationship for Incentive
With Reward and Penalty - Specific Case

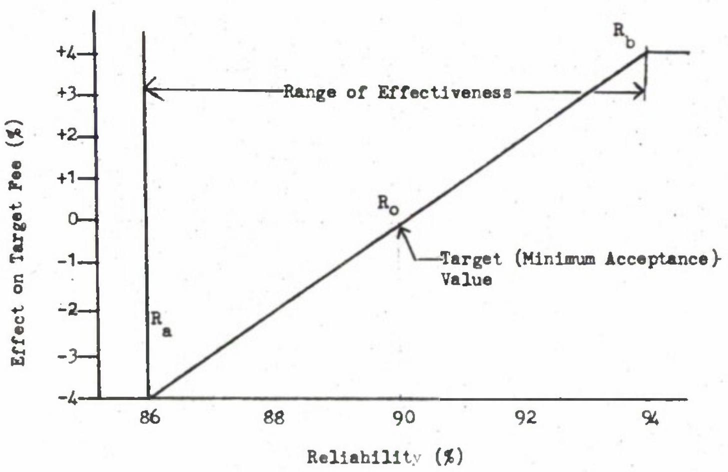

Figure 5

Demonstration of the target (minimum acceptance) value produces no effect on target fee, i.e., the six percent fee is awarded. Failure to demonstrate the target value produces a gradual reduction in fee to a value of total fee equal to two percent. The computation of fee effect is obtained from the product

$$\frac{R - R_o}{R_o} \times \frac{R_o}{R_b - R_o}$$

where R = Demonstrated Reliability

R_o = Target (minimum acceptance) Value

R_b = Reliability Objective

Using our previous values and Figure 5, Table I can be constructed to determine the impact by various R values.

Effect on Fee by Various R Values

R(%)	$\frac{R - R_o}{R_o}$	$\frac{R_o}{R_b - R_o}$	Effect on Fee	Fee Range (%)	Total Fee Paid (%)
86	-4/90	90/4	-1	4	2
87	-3/90	90/4	-3/4	4	3
88	-2/90	90/4	-1/2	4	4
89	-1/90	90/4	-1/4	4	5
90	0/90	90/4	0	4	6
91	1/90	90/4	+1/4	4	7
92	2/90	90/4	+1/2	4	8
93	3/90	90/4	+3/4	4	9
94	4/90	90/4	+1	4	10

Table I

Underlying the reliability incentive situation is the question of the probability of demonstrating reliability values within the constraints and framework of the demonstration model. Since statistical sampling of at least the time domain is involved in any demonstration problem, there exists Type I and Type II errors (producer and consumer risks). Furthermore, to minimize his risk of not demonstrating specific reliability values or maximize his probability of receiving increased fee through incentive provisions, a contractor will have to consider designing for increased reliability beyond the range of reliability interest. For example, assume a fixed test time Poisson model, where total allowable test time is set at two multiples of desired equipment MTBF (minimum acceptance reliability). If only one failure is permitted during this test time, and if a contractor submitted for demonstration an equipment which had an MTBF equal to the target (minimum acceptance) MTBF, he would have only a 41% chance of obtaining maximum fee. He would have to configure an equipment which had an MTBF of approximately twice the value of the target MTBF in order to increase the probability to 72%. Obviously, this destroys the intent of the incentive.

The problem, then, is how to provide a suitable arrangement such that various values of MTBF may be demonstrated with stipulations of incentive for each of these values. As an illustration, Table II, which is based on the Poisson Sequential Test (PST)[1], is provided:

[1] See Section VI, Reliability Decision-Making, Construction and Application of Probability of Acceptance Curves for discussion on PST criteria.

MTBF Demonstration: Accept-Reject Criteria

Risk Level = 2%

Discrimination Ratio = 3/2

Total Observed Failures	Total Test Time* For Reject (Equal or Less)	Total Test Time* For Accept (Equal or More)
0	-	2.3
1	-	3.9
2	-	5.3
3	-	-
4	2.65	-
5	3.6	-
6	4.8	5.85
7	5.85	-

*Total test time is in total hours of satisfactory operating time and is expressed in multiples of minimum acceptance reliability (MTBF).

Table II

The test would proceed according to the specified Accept-Reject Criteria of Table II (or similar table) until such time that an Accept or Reject decision is reached. Assuming that an Accept decision is attained, the contractor may elect to continue the test up to a pre-established cut-off. Whatever point he elects to stop testing, say at Time t*, the number of failures that have occurred by that time, say r, is used to solve the following equation:

$$C(r;\theta_o;t^*) = \sum_{x=0}^{r} \frac{e^{-t^*/\theta_o} \left(\frac{t^*}{\theta_o}\right)^x}{x!}$$

The alternatives for incentive would be:

a. If $c(r;\theta_o;t^*) \leq 5\%$, award maximum incentive.

b. If $c(r;\theta_o;t^*) \leq 10\%$, award intermediate incentive.

c. If $c(r;\theta_o;t^*) \leq 15\%$, award minimum incentive.

As further illustration, assume a minimum acceptance reliability of 200 hours MTBF. Since the discrimination ratio of Table II is 3/2, the upper limit will be 300 hours MTBF. The range of effectiveness, then, is 200 to 300 hours MTBF. Assume that an Accept decision was reached, Table II at Total Observed Failures = one in 780 hours of test time (3.9 x 200). In order for the contractor to obtain maximum incentive for reliability (alternative a), he would have to accomplish an additional 645 hours of satisfactory testing with no additional failures. This was determined by the solution of the above equation with r = 1, $\theta_o = 300$ and $c(r;\theta_o;t^*) \leq 5\%$. An alternate (and easier) method would be to scan the Poisson tables until a U was found with x = 1 and c(x) = .05. It will be found that U = 4.75 at these values. Then proceed as follows to find t* (total test time):

$$U = 4.75 = \frac{t^*}{\theta_o}$$

where $\theta_o = 300$

therefore, $t^* = 300(4.75)$
$= 1425$ hours

But, 3.9(200 hours) = 780 hours test time has been accomplished with one failure. Therefore, the additional test time while experiencing no additional failures necessary to capture maximum incentive will be (1425 - 780) = 645 hours.

Table III provides the Accept-Reject Criteria of Table II together with the additional failure-free test time at each Accept decision point necessary to attain the incentive indicated. Note that no additional fee is provided beyond the third decision point (i.e., Failures = 2). It should be realized that any number of similar plans can be generated as a result of selecting different risk levels and discrimination ratios (incentive range); what is emphasized here is the general technique that is involved.

The attractiveness of increased fee from reliability may be diminished by the need to expend additional funds and time to insure a reasonable chance of obtaining maximum fee for reliability. In a multi-incentive contract where cost and schedule incentives are separately identified and given considerable weight, while reliability is submerged as one of several performance characteristics, a contractor's interest may lag in improving his fee position through increased reliability.

One method to sustain interest in reliability is to make all incentive fees for performance, schedule, cost, etc., contingent upon the reliability demonstrated. Mathematically,

$$T(\text{total fee}) = f_1\ (R;\ R_o;\ R_d)\ \ f_2\ (S;C;--)$$

Where $f_2(S;C;--)$ is the fee paid exclusive of the effects of reliability.

If the incentives for cost, schedule, etc., are additive exclusive of the effects of reliability, the total incentive fee is simply:

MTBF Demonstration Accept-Reject Criteria With Incentive

Risk Level = 10%   Minimum Acceptance MTBF = 200 Hours   Discrimination Ratio = 3/2

Total Observed Failures	Total Test Time for Reject (Equal or Less)	Total Test Time for Accept (Equal or More)	Additional Test Time, With No Additional Failures to Capture Incentive Indicated: Maximum Incentive	Intermediate Incentive	Minimum Incentive
0	---	460	440	230	110
1	---	780	645	390	225
2	---	1060	830	500	350
3	---	---	---	---	---
4	530	---	---	---	---
5	720	---	---	---	---
6	960	1170	---	---	---
7	1170	---	---	---	---

Table III

$$\left(\frac{R - R_o}{R_o}\right) \times \left(\frac{R_o}{R_b - R_o}\right) \times \left(\sum F_s + F_c + \ldots\right)$$

+ Value of Reliability Incentive = Total Incentive Fee

Where F_s, F_c, etc. are the incentive fees for schedule, cost, etc.

When the demonstrated or achieved reliability is equal to the reliability objective, a total incentive fee is simply the maximum allowed fee. When the demonstrated reliability is equal to the target or minimum acceptance reliability, no incentive fee is paid and total fee equals target fee. Conceivably, no incentive fee could result even if demonstrated reliability was in excess of target reliability. This situation would arise if a contractor failed to satisfy the requirements which permit the payment of F_s, F_c, etc.

A numerical example might illustrate the implications of the suggested model. Assume a target fee of 6%, a maximum fee of 14%, schedule and cost incentives with weights 30% and 25%, respectively. Assume further that desired reliability and target reliability are 98% and 90%, respectively, with a linear incentive. If the requirements for schedule and cost payments are satisfied, the total incentive and total fee are as given in Table IV.

Example of Total Fee Computations in a Multi-Incentive Situation

(I) Demonstrated Reliability (%)	(II) $\frac{R - R_o}{R_o}$	(III) $\frac{R_o}{R_b - R_o}$	(IV) Value of Rel Incentive (%)	(V) Value of Cost Incentive (%)	(VI) Value of Schedule Incentive (%)	(V + VI) (%)	Total Value of Incentive (%)	Total Fee (%)
90	0	90/8	0	2.0	2.4	4.4	0	6.0
92	2/90	90/8	0.9	2.0	2.4	4.4	2.0	8.0
94	4/90	90/8	1.8	2.0	2.4	4.4	4.0	10.0
96	6/90	90/8	2.7	2.0	2.4	4.4	6.0	12.0
98	8/90	90/8	3.6	2.0	2.4	4.4	8.0	14.0

Table IV

C O P Y

HEADQUARTERS
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
ANDREWS AIR FORCE BASE
Washington 25, D.C.

REPLY TO
ATTN OF: SCKP

19 November 1963

SUBJECT: Reliability Programs (AFR 80-5)

TO: ASD SSD BSD ESD
(Director of Procurement)

1. In a recent general inspection the AFSC Inspector General reported that:

"Two hundred contracts were reviewed and only two contained dollar penalties for failure to attain required reliability in either the contract or the statement of work that pertained to reliability. Few contracts contained specific Mean Time Between Failure (MTBF) figures or a clearly stated mathematical model for reliability computation."

2. Your attention is invited to AFR 80-5 and in particular paragraphs 4f, 6c and e. To assure that this Command fulfills its responsibilities under this program, it is requested that every reasonable effort be made to negotiate the appropriate factors into new contracts and, where not now in evidence, to negotiate/renegotiate adequate dollar penalties and administrative requirements to satisfy the calculations of Mean Time Between Failure factors.

FOR THE COMMANDER

/s/ Herbert L. Repetti

HERBERT L. REPETTI
Deputy Director of Procurement
DCS/Procurement & Production

C O P Y

Attachment 1

Excerpts From
ARMED SERVICES PROCUREMENT REGULATION
Section VII, Paragraph 7-103.5

Paragraph 5. INSPECTION

(a) All supplies (which term throughout this clause includes without limitation raw materials, components, intermediate assemblies, and end products) shall be subject to inspection and test by the Government, to the extent practicable at all times and places including the period of manufacture, and in any event prior to acceptance.

(b) In case any supplies or lots of supplies are defective in material or workmanship or otherwise not in conformity with the requirements of this contract, the Government shall have the right either to reject them (with or without instructions as to their disposition) or to require their correction. Supplies or lots of supplies which have been rejected or required to be corrected shall be removed or, if permitted or required by the Contracting Officer, corrected in place by and at the expense of the Contractor promptly after notice, and shall not thereafter be tendered for acceptance unless the former rejection or requirement of correction is disclosed. If the Contractor fails promptly to remove such supplies or lots of supplies which are required to be removed, or promptly to replace or correct such supplies or lots of supplies, the Government either (i) may by contract or otherwise replace or correct such supplies and charge to the Contractor the cost occasioned the Government thereby, or (ii) may terminate this contract for default as provided in the clause of this contract entitled "Default." Unless the Contractor corrects or replaces such supplies within the delivery schedule, the Contracting Officer may require the delivery of such supplies at a reduction in price which is equitable under the circumstances. Failure to agree to such reduction of price shall be a dispute concerning a question of fact within the meaning of the clause of this contract entitled "Disputes."

(c) If any inspection or test is made by the Government on the premises of the Contractor or a subcontractor, the Contractor without additional charge shall provide all reasonable facilities and assistance for the safety and convenience of the Government inspectors in the performance of their duties. If Government inspection or test is made at a point other than the premises of the Contractor or a subcontractor, it shall be at the expense of the Government except as otherwise provided in this contract: Provided, That in case of rejection the Government shall not be liable for any reduction in value of samples used in connection with such inspection or test. All inspections and tests by the Government shall be performed in such a manner as not to unduly delay the work. The Government reserves the right to charge to the Contractor any additional cost of Government inspection and test when supplies are not ready at the time such inspection and test is requested by the Contractor or when reinspection or retest is necessitated by prior rejection.

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Attachment 2

Acceptance or rejection of the supplies shall be made as promptly as practicable after delivery, except as otherwise provided in this contract; but failure to inspect and accept or reject supplies shall neither relieve the Contractor from responsibility for such supplies as are not in accordence with the contract requirements nor impose liability on the Government therefor.

(d) The inspection and test by the Government of any supplies or lots thereof does not relieve the Contractor from any responsibility regarding defects or other failures to meet the contract requirements which may be discovered prior to acceptance. Except as otherwise provided in this contract, acceptance shall be conclusive except as regards latent defects, fraud, or such gross mistakes as amount to fraud.

(e) The Contractor shall provide and maintain an inspection system acceptable to the Government covering the supplies hereunder. Records of all inspection work by the Contractor shall be kept complete and available to the Government during the performance of this contract and for such longer period as may be specified elsewhere in this contract.

Paragraph 11. DEFAULT

(a) The Government may, subject to the provisions of paragraph (c) below, by written notice of default to the Contractor, terminate the whole or any part of this contract in any one of the following circumstances:

(i) if the Contractor fails to make delivery of the supplies or to perform the services within the time specified herein or any extension thereof; or

(ii) if the Contractor fails to perform any of the other provisions of this contract, or so fails to make progress as to endanger performance of this contract in accordance with its terms, and in either of these two circumstances does not cure such failure within a period of 10 days (or such longer period as the Contracting Officer may authorize in writing) after receipt of notice from the Contracting Officer specifying such failure.

(b) In the event the Government terminates this contract in whole or in part as provided in paragraph (a) of this clause, the Government may procure, upon such terms and in such manner as the Contracting Officer may deem appropriate, supplies or services similar to those so terminated, and the Contractor shall be liable to the Government for any excess costs for such similar supplies or services: Provided, That the Contractor shall continue the performance of this contract to the extent not terminated under the provisions of this clause.

(c) Except with respect to defaults of subcontractors, the Contractor shall not be liable for any excess costs if the failure to perform the contract arises out of causes beyond the control and without the fault or negligence of the Contractor. Such causes may include, but are not restricted to, acts of

God or of the public enemy, acts of the Government in either its sovereign or contractual capacity, fires, floods, epidemics, quarantine restrictions, strikes, freight embargoes, and unusually severe weather; but in every case the failure to perform must be beyond the control and without fault or negligence of the Contractor. If the failure to perform is caused by the default of a subcontractor, and if such default arises out of causes beyond the control of both the Contractor and subcontractor, and without the fault or negligence of either of them, the Contractor shall not be liable for any excess costs for failure to perform, unless the supplies or services to be furnished by the subcontractor were obtainable from other sources in sufficient time to permit the Contractor to meet the required delivery schedule.

(d) If this contract is terminated as provided in paragraph (a) of this clause, the Government, in addition to any other rights provided in this clause, may require the Contractor to transfer title and deliver to the Government, in the manner and to the extent directed by the Contracting Officer, (i) any completed supplies, and (ii) such partially completed supplies and materials, parts, tools, dies, jigs, fixtures, plans, drawings, information, and contract rights (hereinafter called "manufacturing materials") as the Contractor has specifically produced or specifically acquired for the performance of such part of this contract as has been terminated; and the Contractor shall, upon direction of the Contracting Officer, protect and preserve property in possession of the Contractor in which the Government has an interest. Payment for completed supplies delivered to and accepted by the Government shall be at the contract price. Payment for manufacturing materials delivered to and accepted by the Government and for the protection and preservation of property shall be in an amount agreed upon by the Contractor and Contracting Officer; failure to agree to such amount shall be a dispute concerning a question of fact within the meaning of the clause of this contract entitled "Disputes."

(e) If, after notice of termination of this contract under the provisions of paragraph (a) of this clause, it is determined that the failure to perform this contract is due to causes beyond the control and without the fault or negligence of the Contractor or subcontractor pursuant to the provisions of paragraph (c) of this clause, such notice of default shall be deemed to have been issued pursuant to the clause of this contract entitled "Termination for Convenience of the Government," and the rights and obligations of the parties hereto shall in such event be governed by such clause. (Except as otherwise provided in this contract, this paragraph (e) applies only if this contract contains such clause.)

(f) The rights and remedies of the Government provided in this clause shall not be exclusive and are in addition to any other rights and remedies provided by law or under this contract.

Paragraph 12. DISPUTES

(a) Except as otherwise provided in this contract, any dispute concerning a question of fact arising under this contract which is not disposed of by agreement shall be decided by the Contracting Officer, who shall reduce his decision to writing and mail or otherwise furnish a copy thereof to the Contractor. The decision of the Contracting Officer shall be final and conclusive

unless, within 30 days from the date of receipt of such copy, the Contractor mails or otherwise furnishes to the Contracting Officer a written appeal eddressed to the Secretary. The decision of the Secretary or his duly euthorized representative for the determination of such appeals shall be final and conclusive unless determined by a court of competent jurisdiction to have been fraudulent, or capricious, or arbitrary, or so grossly erroneous as necessarily to imply bad faith, or not supported by substantial evidence. In connection with any appeal proceeding under this clause, the Contrsctor shall be afforded an opportunity to be heard and to offer evidence in support of its appeal. Pending final decision of e dispute hereunder, the Contractor shall proceed diligently with the performance of the contract and in accordance with the Contracting Officer's decision.

(b) This "Disputes" clause does not preclude consideration of law questions in connection with decisions provided for in paragraph (a) above: Provided, That nothing in this contract shall be construed as making final the decision of any administrative official, representative, or board on a question of law.

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13. ABSTRACT

The ESD Reliability and Maintainability (R/M) Staff originally prepared a series of pamphlets dealing with R/M matters during 1963-64. These have now been combined into a single handbook for ready reference and assimilation by ESD personnel associated with R/M programs. Each section of this handbook deals with a particular problem area in R/M matters and suggests methods of initiating and operating an R/M program. The material covered ranges from the basic elements of establishing a program thru the engineering requirements to be evaluated in design reviews. The overall operations involved in monitoring of a contractors program are defined. Several sections deal with the mathematical aspects of Reliebility decision making including construction of probability of acceptance curves. Specific areas covered in thie TDR are listed in the Table of Contents.

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Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Command & Control Systems						
Reliability (R)						
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